Instituto Superior de Engenharia do Porto

DEPARTAMENTO DE ENGENHARIA MECÂNICA

INTEGRATION OF THE PROJECT TEAM IN THE CLASSIC MAINTENANCE CYCLE

Luís Miguel Barbosa da Cruz

2015

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1000686

Dissertação apresentada ao Instituto Superior de Engenharia do Porto para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação do Doutor Francisco José Gomes da Silva, Professor Adjunto do Departamento de Engenharia Mecânica do ISEP.

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Acknowledgements / Agradecimentos

This thesis represents the culmination of my academic career, which itself represents a long and not always easy path of growth and continuous demand.

It is my belief that this path is made with perseverance, respect for others and team spirit.

In this regard, I must thank all those who shared with me experiences at professional level, with special emphasis on my colleagues and managers at Continental Mabor for all the support provided in the elaboration of the thesis I am presenting.

I must also enhance the total support given by “my teacher” Francisco Silva. Thank you so much.

Thus, I cannot fail to thank my parents for education and bases of responsibility, integrity and demand instilled from an early age that, today, allow me to face each challenge as it only, a challenge to overcome.

Thanks also to my sister, by the complicity and unconditional support.

Finally, and most of all, I am grateful to my wife. From you Cláudia, I thank the motivation, support and, above all, the patience!

Alone, this route would have been impossible!

Resumo

A manutenção é uma área extremamente importante, principalmente na indústria. Devidamente organizada, permitirá um fluxo produtivo devidamente planeado e executado, que permitirá a qualquer empresa manter o nível de facturação desejado e o prazo de entrega acordado com os clientes. De outra forma, poderá originar o caos.

No entanto, os desafios de gestão da produção mais correntes, nomeadamente através do Lean Manufacturing, passam a exigir um pouco mais do que uma simples manutenção. Torna-se obrigatório fazer análises económicas que permitam averiguar quando cada equipamento passa a exigir custos de manutenção excessivos, os quais poderão obrigar a um recondicionamento mais acentuado do equipamento, o qual pode passar inclusivamente por uma melhoria da sua performance. Nestes casos, terá que existir uma "cumplicidade" entre a Direcção de Produção e a Manutenção, no sentido de averiguar o melhor momento para proceder a uma melhoria do equipamento, numa perspectiva de funcionamento global em linha de produção, adaptando-o à performance que será exigida ao conjunto.

Neste domínio, o Projecto passa a prestar um serviço valiosíssimo à empresa, integrando-se no conjunto Produção + Manutenção, criando valor na intervenção, através do desenvolvimento de um trabalho que permite não só repor o estado natural da produção, mas sim promover uma melhoria sustentada da mesma. Este trabalho pretende reflectir e avaliar a relevância do Projecto neste tipo de operações, contribuindo de uma forma sistemática e sustentada para a melhoria contínua dos processos de fabrico. É apresentado um caso de estudo que pretende validar todo o desenvolvimento anteriormente realizado na matéria.

Palavras-chave

Manutenção, Gestão da Manutenção, Produção, Lean-Manufacturing, Projecto, Projecto integrado na Manutenção.

Abstract

Maintenance is an extremely important field of work, mainly in the industry. Duly organized will allow a properly planned and carried out productive flow, which will allow any company to maintain the desired level of billing and the delivery time agreed with customers. Otherwise, could lead to chaos.

However, the most common production managing challenges, in particular through Lean Manufacturing, will require a little more than a simple maintenance. It becomes mandatory to do economic analyses which become feasible to find out when each equipment shall require excessive maintenance costs, which might advise to perform more remarkable equipment reconditioning, passing even by an improvement in its performance. In these cases, it must be an involvement between the Direction of Production and Maintenance, in order to find out the best time to proceed to the equipment upgrade, in terms of overall operation on production line, adjusting it to the performance that will be required to set.

In this field, Design will provide an invaluable service to the company, joining in the Production + Maintenance areas, creating value in the intervention, through the development of a job that allows not only restoring the natural state of production, but rather promoting a sustained improvement of the same. This work aims to reflect and assess the relevance of the Design in this type of operations, contributing to a systematic and sustained manner to the continuous improvement of manufacturing processes. A case-study is presented in order to illustrate how the design can help the maintenance function, upgrading significantly the equipment's performance, validating all the development done in this area through this work.

Keywords

Maintenance, Maintenance Management, Production, Lean-Manufacturing, Design, Design integrated with Maintenance.

List of Symbols and Abbreviations

ABC - Activity Based Costing

ABS - Anti-lock Braking System

AoA - Analisys of Alternatives

CBDAS - Continental Basic Data Acquisition Software

CBS - Cost Breakdown Structure

CER - Cost Estimating Relationship

CIP - Continuous Improvement Process

CM - Conti Machinery

CMIP - Continental Mabor Indústria de Pneus SA

CPP - Continental Pneus Portugal

ESP - Electronic Stability Control

ESS - Electronic Suspension System

FMEA - Failure Mode and Effects Analysis

ICT - Information and communication Technologies

ICT - Information and Communication Technologies

ITA - Indústria Têxtil do Ave

KM - Carcass Construction Machine

KPI - Key Performance Indicator

LCC - Lifecycle Cost Concept

MES - Machine Equipment Standard

MTBF - Mean Time Between Failure

MTTF - Mean Time to Failure

NPW - Nissan Production Way

OEE - Overall Equipment Efficiency

OPC - Object Linking and Embedding for Process Control

PDCA - Plan-Do-Check-Act Methodology

PEMS - Plant Engineering Maintenance System

PLC - Programmable Logic Controller

PLT - Passengers and Light Trucks

PU - Production Unit

R&D - Research and Development

TBM - Tire Building Machine

TC - Total Cost

TCS - Traction Control System

TPM - Total Productive Maintenance

USA - United States of America

UUHP - Ultra Ultra High Performance

WBS - Work Breakdown Structure

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1. *Introduction*

1.1. Background

Any company is only viable if it is competitive. The competitiveness based on a business integrated management, which passes through the teamwork of the various sectors those integrate it. Industrial companies are focused on production, which depends on its own organization, and the whole environment that surrounds it, from product design, to the quality assurance systems. For goods to be produced are needed available and appropriate equipment's to the adopted production system. The preservation operation of this equipment is vital to fulfil the production plans, as required by the commercial department, one hand, and stipulated and guaranteed by the scheduling department, on the other. In addition, the continued demand of increasing productivity means that the equipment is operated in its limit, which requires a greater effort to preserve its operating status. However, a careful costs analysis of preserving the functioning equipment, as well as the production needs of the customers. Just like any other good, if maintenance costs pass to be significant, the intervention will necessarily have to follow other principles: or replacement equipment through the acquisition of a new one, or its deep reconditioning, simultaneously adapting to new needs and the production capacity of the line in which it is embedded.

If the definition of needs in terms of production targets to be achieved is carried out by the Production Manager, the aggregate concept in these requirements should be made by the Project Team, the one that has the necessary 'know-how" for selecting the best way to achieve those objectives.

This leads to a new Maintenance management style, where the Project Team is particularly important, as it can bring high added value to each maintenance intervention, through the enhancement of that intervention in terms of added value for the company, improving performance assembly. This system requires the appropriate integration of the Project Team in the areas of Production and Maintenance, with a value creation in terms of productivity, which can be extremely significant for the global business.

1.2. Goals

This work had the main objective of carrying out a study about the advantages offered by the integration of the “Project Team” in activities traditionally managed by Production and Maintenance in a large industrial company. Thus, may be deemed that the main objectives are to:

- Identify how the “Project Team” can be useful in maintenance operations within a large company;
- Establish the most appropriate management format for work integration in the best possible way;
- Those are the real advantages of this integration.

For achieving the above objectives, it became necessary to:

- Analyse the potential operation of the company with different maintenance systems usually applicable in the industry;
- Analyse the company organization chart and understand the relationship between different areas;
- Study the needs in terms of Production and Maintenance within the company;
- Survey the situation experienced several years ago, when this integration did not exist;
- Survey the current situation since integration of the “Project Teams” is working;
- Analyse differences in terms of economic performance and the integration of some sectors;
- Draw conclusions and establish a model that can be successfully applied by any other company.

1.3. *Methodology*

The preparation of this work followed the methodology set out below:

- Study about the state of the art concerning this issue;
- Run a complete survey of the real situation several years ago, in this field;
- Perform the study analysis of the current situation, considering the “Project Team” as a valuable aid in the equipment definition and production lines regeneration;
- Establish the respective differences, advantages and limitations resulting from the implementation of this system, regarding operational purposes;
- Carry out a brief economic study on the advantages of the current system;
- Present a case study that can link the “Project Team” integration in the traditional Maintenance cycle;
- Develop a model that easily extrapolate this experience to other companies;
- Formulating this thesis.

1.4. Structure

The structure of this work is mainly based on two parts: an initial Literature Review, which aims to frame the reader with the issues involved in this work, by reviewing the technical and scientific developments published in scientific books or journals dedicated to these matters, and the Practical work itself, with reference to how the work evolved, methodologies used, the developments carried out, results and conclusions.

2. Literature Review

2.1. Maintenance: Brief Introduction

2.1.1. "Maintenance" Role

According to NP-EN-13306: 2007, maintenance is the combination of all technical, administrative and management activities, during a good's life cycle designed to keep it or replace it, to a state which allow the required function. According to the same standard, the maintenance management are all activities that determine the objectives, the strategy and the responsibilities related to the safeguarding and implementing them by various means such as planning, control and supervision of the maintenance and improved methods in the organization, including the economic aspects.

According to Kardec *(Kardec et al, 2003),* maintenance is extremely important in industry in order to produce the largest number of products that the equipment can manufacture without breakdowns / failures.

2.1.2. Brief History about Maintenance

To find out how the Maintenance evolved, one must go back in time to the early twentieth century to know how it was seen and used (Figure 1). The historical evolution of Maintenance is divided into four phases.

Below are showed some of the most memorable moments of the maintenance evolution:

I – 1914: the maintenance mattered little, was a secondary consideration in the production process, the industries of that time did not have teams specialized in maintenance and industries worked to make the best machines production until they have a failure or stop permanently.

From the First World War, industries in a generally manner, willing to maintain a minimum production, created an organ / team subordinate to Production. The basic goal was to make equipment corrective maintenance, namely when the equipment for some reason stopped producing, maintenance was driven to make proper repairs, thus returning to the production process, which at that time was enough. Demand for services until then was little, because the machines are oversized and robust, which guarantee a long service life.

*Figure 1 - Steam Machine of 1800's (**http://www.adazi.1v/page/150**)*

II - The situation presented in the first phase was the time of "fault-fix", remaining like that until the 30s when, motivated by the Second World War, the need to rapidly increase production corresponding to the supply of a growing demand, the industries in their highest decisions levels decided to create a maintenance department, so that there was a concern not only to correct the faults but also prevent them. At that time was begun to think about how we could keep the sector from there on, *ie* that maintenance should be done, so that the machines could produce the largest number of parts.

III - From 1940 to 1970, with the development of commercial aviation, there was an expansion of preventive maintenance criteria, since there was not the possibility to perform corrective maintenance on an aircraft during flight. This stage is considered the most important of all, since enabled the maintenance to have more quality. The maintenance started to be seen in another way, it grew up from a function of repairing the equipment for a more qualified function (more technical) as is the case of equipment failure analysis, anticipating problems or failures.

In the late sixties early seventies, the first computers appeared, being extremely huge (as big as houses), very slow and with few functions.

IV - From 1970 to the present, with the industry rise and the computers expansion, being faster with powerful software, maintenance has been inserted into the most sophisticated processes, such as control and analysis, used in everyday life. Servicing is not just using the tool boxes for defective machines repair, but also anticipating failures and determining the best and most economic periods for the implementation of preventative maintenance, which in most cases is no longer just based on time.

These criteria are also known as informative controllers that aim to predict or monitor the equipment condition, putting the maintenance in a controlled situation and therefore more economical for companies, with impact on production and especially safer for workers and the environment.

The phase IV appeared early in the seventies with the existing technology at that time. With computers development, it has been improved and adapted to maintenance.

2.1.3. Evolution of the Maintenance Function

In the seventies appeared “conditioned” preventive maintenance, consisting of performing maintenance on components only when needed. It is a preventive maintenance subordinated to a predetermined event type (self-testing) where the information is given by a sensor so that there is wear, vibration, noise or other indicator that can reveal equipment degradation.

Total productive maintenance, also known by TPM, appeared in the 1980s in Japan (the TPM will be described further on).

The total productive management appeared in the 1990s, and it is a management tool for the elimination of industrial losses.

In the year two thousand upsurge the e-Maintenance concept which results from the ICT (Information and Communication Technologies) application to the industry, within the maintenance strategy.

2.2. Maintenance from a perspective of Production Optimization

By enhancing the effects of a careful and planned maintenance in an industrial park we are, by this way, enhancing also the production process optimization.

Reliable equipment, with high production levels and with production stops reduced just for preventive maintenance periods, represent high levels of productive availability or Overall Equipment Efficiency (OEE) and guarantee an output whose values depend only on the production department scheduling.

It can be therefore conclude that a strong bet in a robust and planned maintenance system is a production levels enhancer factor.

2.2.1. "Lean" Methodology

Lean means thinner (training people so that they are aware that everything that spoils has costs, and does not make investments without anticipated analysis) in order to not make expenditures that are not needed and increasing productivity with the same resources. The implementation of Lean in a company helps to reduce costs in maintenance, production, logistics and administrative services, and in the human resources.

More than implement it, this philosophy must be kept, and to keep it, constant innovation is needed.

Lean appeared in the United States of America in the early twentieth century by Frederick Taylor and it was applied to industry for a man who had a vision would change the world, this man was Henry Ford. Ford wanted to produce a car at low cost so that all the people had possibility to have one. To lower the car cost he had to increase the daily production, being a single model and using just one colour, black.

Ford implemented the assembly line methodology, where the work was sequential from the beginning up to the exit of the factory; in this process, each worker had only one function which on the one hand it was good, because the worker was earning more and more experience.

From the worker's point of view were stressful tasks, they could not make mistakes or losses of time with the risk of decreasing production and these tasks were performed mechanically by workers (without thinking what they were doing).

By this system, they were able to reduce the assembling time of the Model T. As an example, in the year 1908, to assemble a full chassis it would take 728 minutes, after five years they were able to mount the same chassis in 93 minutes (Ntuen, 1991).

It was only possible to reduce this time due to deletions of wastes, intermediate times and improved worker's performance, the need to produce the largest number of parts without any errors and the need to create a quality control in each assembly line section (Ntuen, 1991).

Through this methodology, Lean philosophy was born without having this name or thought.

2.2.2. Continuous Improvement

Three main methods for improvement, one a continuous improvement tool and the others methods for finding root causes, are touched onto this thesis. To ensure comprehension of these methods, a respective explanation is needed.

2.2.2.1. Deming Cycle

W.E. Deming originally developed the cycle as "Plan-Do-Check-Act" (PDCA), but later changed to study as he found it to better illustrate his intention with that step. He also liked to call it the Shewart cycle after Walter A. Shewart from who he was inspired to the PDCA (Figure 2).

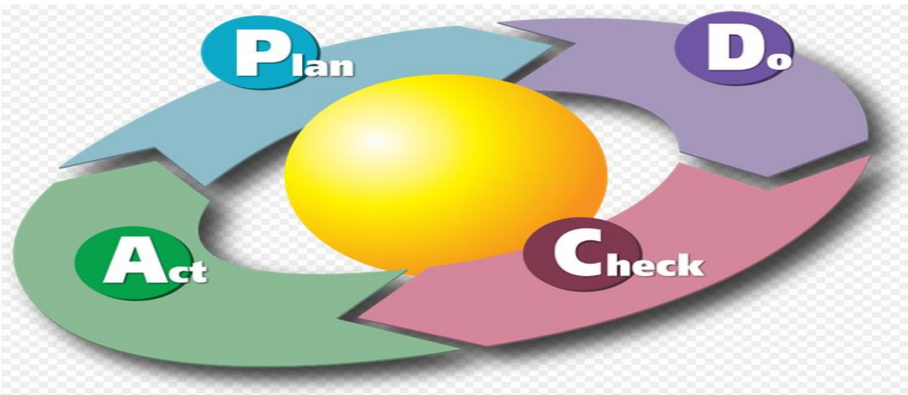

*Figure 2 - PDCA Cycle Illustration (**http://en.wikipedia.org**)*

The cycle is developed as a method to promote the Continuous Improvement Process (CIP) (Klefsjö, 2001). It is divided into four general steps, which are to be taken in order and, as the name suggests, it is a cycle which is therefore repeated.

When a problem is initially addressed, the source needs to be searched. To find potential sources, existing methods such as Ishikawa diagram or FMEA can be applied. After sorting out the potential candidates and collecting all relevant data, effective objectives need to be established. This means the Plan stage. In the next step, Do, the objectives are executed in appropriate scale. To confirm an improvement, the new processes are studied (step three) and compared to the original (check).

Depending on the outcome of the implementation, the fourth step involves acting accordingly. If the sought after results were achieved, the processes need to be standardized, else we learned from the mistakes and the cycle is continued from start again with new insight (Ntuen, 1991).

2.2.2.2. Ishikawa diagram

The Ishikawa diagram, also called a fishbone diagram due to its appearance, is a diagram developed to find root causes to a chosen problem. It is named due to its inventor, Kaoru Ishikawa, who first started using the method in 1943 at Kawasaki Steel Works in Japan (Klefsjö, 2001). It is built with the effect or problem at the right, and its possible causes to the left. To begin with, it is not always easy to come up with causes to a problem, which is why in industrial settings the causes can most often be divided into some of seven major categories to start from (Klefsjö, 2001). These categories are management, man, method measurement, machine, material and Mother Nature, as we can see in the illustration bellow. To find possible causes to continue analysis with, the fishbone (Figure 3) is then branched out further with primary and secondary causes until the root causes are defined (Inozu, 1991).

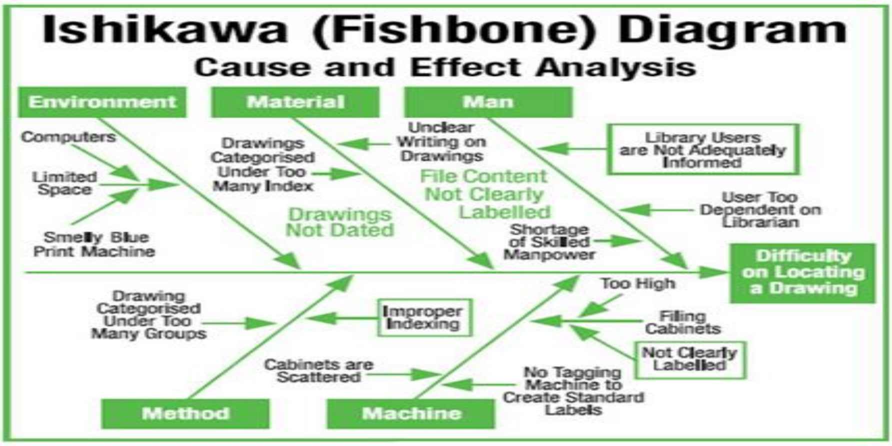

Figure 3 - Ishikawa Diagram Illustration (http://www.apo-tokyo.org)

2.2.2.3. The Five Whys

The Five Whys (Figure 4) is a simple question-asking method aimed at discovering root causes. It can result in very specific root causes if combined with an Ishikawa diagram. Despite its simplicity it should not be taken too lightly, as it has to be used properly and without jumping to conclusions or assumptions.

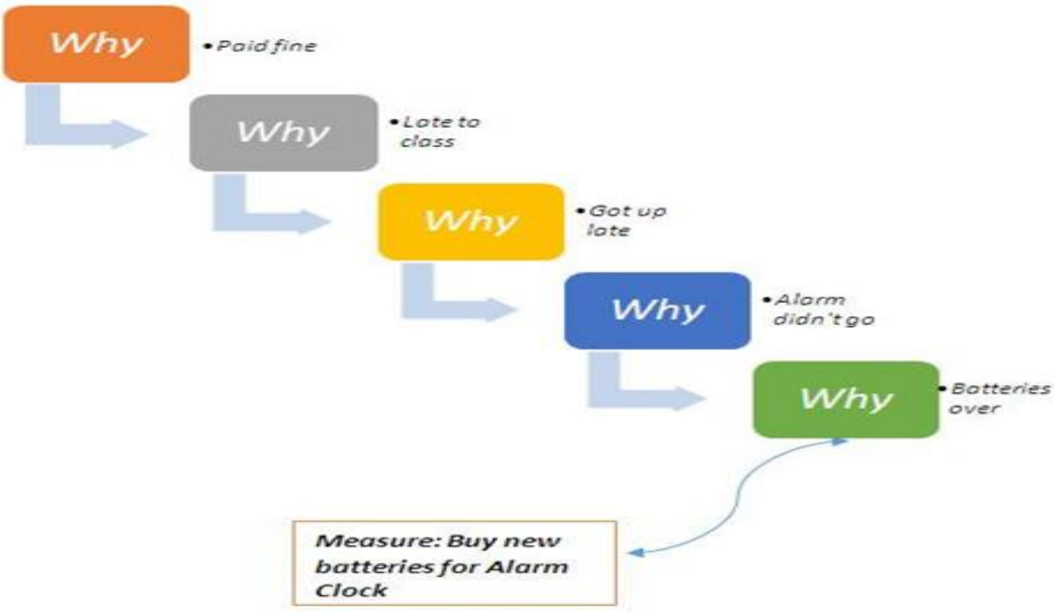

Figure 4 - Five Whys diagram example (http://www.mbaskool.com)

This is a simple example, but it shows how steps should be taken one at time. Also, this could be expanded to more steps, but in most cases Five Whys can be enough to find the root cause.

2.2.3. Maintenance Management Systems

2.2.3.1. Breakdown Maintenace

According to Kardec (Kardec, 2003) corrective maintenance is the correction of the unplanned breakdown after a problem affecting in some or all of the equipment, and it can be divided into two groups, namely planned and unplanned corrective maintenance.

According to Xenos (Xenos, 1998), this process causes a great cost to the company on the machines maintenance.

The higher cost is when production stops, having costs with the stop itself (non-production), being concerned to quality and delivery times of final products to customers.

Planned corrective maintenance (deferred Maintenance) it is a programmed correction / repair through predictive or detective methods, until the intervention is possible, without affecting directly the production (Kardec, 2003).

2.2.3.2. Preventive Maintenance

Preventive maintenance is the maintenance operations carried out with the intention to reduce or avoid equipment breakdown. For this purpose we use an advanced plan, with defined time intervals, regardless of the actual need, which aims to act as preventive care to avoid failures (Kardec, 2003).

2.2.3.3. Predictive Maintenance

Predictive maintenance is when the adjustments on the machines or equipment are made just when they need them, but without they break down or stop. With a direct and constant monitoring, it is possible to predict failures and know when it will be necessary to do an intervention (Kardec, 2003).

2.2.4. TPM – Total Productive Maintenance

Productive Maintenance appeared in the United States of America in the late forties early fifties. This concept was characterized by the development of systematic preventive maintenance techniques to improve the equipment reliability.

The Total Productive Maintenance (TPM) is not more than the initial “American Productive Maintenance” concept modified and improved to fit the Japanese industrial environment.

In 1953, a group of 20 Japanese businessmen gathered to do research who moved in 1962 to the United States of America focused in observing "American productive maintenance". This mission gave rise to the creation of the Japan Institute of Plant Engineers (JEEP), predecessor of the Japan Institute of Plant Maintenance, created in 1969. The Ninppondenso (supplier of components to Toyota) was the first Japanese company to introduce preventative maintenance in the equipment of its production lines.

According to Willmott and Mccarth (2001), the TPM is a philosophy or a way of thinking around maintenance, which means a new concept of how to keep an installation or equipment.

The TPM is a management method that identifies and eliminates losses existing in the productive processes, maximizing the use of industrial assets and ensuring the generation of high quality products at competitive costs, knowledge developments able to re-educate people to preventive actions and continuous improvement, ensuring the reliability of the equipment and the ability of the processes, without additional investments.

According to Ribeiro (2007), translated into the English language TPM Total Productive Maintenance:

Total – means that all employees are involved in all activities in order to eliminate all accidents, defects and failures (waste).

Productive – means that the actions are performed during continuous production, so that the problems for the productions are minimized.

Maintenance – maintain a good condition of the equipment repairing, cleaning and greasing.

Regarding these procedures, you can ramp up production and simultaneously lift the morale and job satisfaction of employees.

The time for maintenance is planned with the production process and together they know the ideal time to stop production and carry out the equipment maintenance. In this way, it is intended to transform or minimizing possible emergency maintenance (corrective maintenance) (Rajan, 2007).

To apply the TPM, first we have to provide the best training to workers both in the maintenance and production area, involving everyone to work as a team and dialoguing among themselves. The workers are the best connoisseurs and equipment status informers, so they can describe and transmit all deficiencies, even before they are damaged.

Regarding the application of TPM philosophy, we can avoid unnecessary expenses, normal in an environment of constant economic change, produce goods without reducing the quality of the same, reduce costs and produce more in less time. Thus, the products are being delivered to customers without defects (Shirose, 2000).

2.2.5. OEE – Overall Equipment Effectiveness

To achieve success in the TPM implementation, there must be a way of measuring how initially processes were and what are the gains achieved with the implementation of the programme.

For such, a performance indicator named OEE (Overall Equipment Efficiency) was created, which measures the productivity of equipment and processes (Pomorski, 1997). In the vast bibliography on this topic, we can find some authors refer to this indicator as Overall Equipment Efficiency and others whom call for Overall Equipment Effectiveness.

The key figure OEE allows visualization of machine related losses. This might seem easy at first, because with a machine theoretically able to run 24 hours a day and 365 days each year we get an amount of products representing the maximum capacity. Due to holidays and managerial decisions as not working on most weekends and so on, the maximum capacity is mostly never exploited.

Therefore, the quotient of the actual number of produced units put up against the maximum capacity yields the effectiveness of the equipment during the chosen time period, being obtained the overall equipment effectiveness (Reitz, 2008). It is important to keep in mind that the OEE is only a measurement of mechanical components. Therefore all losses, even those influenced by human aspects, such as change-overs, should be considered as the only interest in the OEE is to see whether the equipment runs according to its capability [Reitz, 2008]. The basic requirement for OEE correct calculation is, of course, accurate data. All mechanical losses need to be recorded for best results.

2.3. Maintenance Policies

Maintenance involves planned and unplanned actions carried out to retain a system in or restore it to an acceptable condition. Optimal maintenance policies aim to minimize downtime and the operations cost. Many practitioners and academicians have tried to address the problem of maintenance policies.

The two basic types of maintenance are:

I - Corrective: Unscheduled maintenance required as a result of failure to restore a system to acceptable performance level.

II - Preventive: Scheduled maintenance required in order to operate a system at an acceptable level of performance.

For complex systems comprising many different components, the actual maintenance problem may be the organization of preventive maintenance work that depends on the critical ages of components, rather than searching for some optimal solution in terms of any precise criterion. This would help reduce the complexity of the problem and help develop heuristics. Often sufficient data may not be available for complex models; if they are not available then the maintenance policies may not be pragmatic. It is not very difficult in practice to develop maintenance models where suitable data is available and adopted policies are realistic (Scarf, 1999) ie, the application of theoretical concepts to the industrial reality is not always easy as result oftentimes of the lack of necessary information and the incompatibility of the production scheduling with the practical application of the theoretical model.

2.3.1. Subjective Approach

This approach is useful in situations where objective data is not available or difficult to obtain. The validity of such approaches is always debatable as it is based on expert opinion, which may be influenced by current maintenance practice rather than being based on the understanding of the current maintenance process. Various models have been proposed that incorporate expert judgment to determine maintenance policies. Scarf (1999) has developed a model that uses subjective data but works like a quantitative model. The model developed in this thesis also employs a similar technique. An integrated approach to maintenance modelling involves the following steps:

I) Problem recognition;

II) Design of data collection;

III) Design of systems for future data collection;

IV) Effective (mathematical) modelling using data collected;

V) Comparison with competitive techniques;

VI) Formulation of revised maintenance policy;

VII) Imparting ownership of models and policy on maintenance managers;

VIII) Economic considerations of new policy;

The author advocates that through such a comprehensive approach, mathematical modelling can be considered successful from a scientific (i.e., modelling) point of view.

2.3.2. Maintenance Based on the Operational Status of the Equipment

Recently, condition monitoring techniques are being adopted by many practitioners (Scarf, 1997).

The competitive market conditions have forced plant management to reduce downtime for routine preventive maintenance. In such cases, the maintenance department inspects the condition of all parts that are due for replacement. If the condition-related variable is below a pre-set (critical) value (which is determined by subjective opinion), then the component is replaced, else it is allowed to operate. Thus, a routine preventive maintenance shut down can be avoided. This also has a psychological effect on the people working in the plant, who would, otherwise, feel uncertain about the state of the plant.

This technique requires a database of all the components replaced on all the machines and their pre-set value. Also a systematic plan must be developed to check and recheck regularly if the state of any component has crossed its pre-set value (beyond safe usage conditions). This would increase the maintenance cost. The fundamental question for condition monitoring of a particular component should be whether this approach will reduce costs in the long run by giving a policy very close to the true optimal one. Since condition-based maintenance helps use all the components for a longer period than fixed maintenance policy, lesser replacements would be required reducing the long-term maintenance costs.

2.3.3. Dynamic Systems for Scheduling Maintenance (Model)

Coyle and Gardiner (1991) have proposed a discrete (integer) system dynamics model of maintenance schedules for submarine operations.

System dynamics models are usually continuous models but the authors have developed a discrete model since the ships are discrete objects. The model addresses the issues of fleet availability and usage during the service life of a submarine. The model computes the number of submarines to be commissioned so that the minimum number of submarines is in service. The feedback system used for the model captures how a force of a given size is likely to meet its operational needs and what policies might guide decision makers to cope with difficulties as and when they arise. The model considers three types of decisions: short term, medium term and long term decisions. The discrepancy between the operational needs (goal) and current availability is used to drive the model decisions.

The short-term decisions deal with the number of submarines in operations, the medium term decisions deal with the maintenance program while the long-term decisions deal with the construction of submarines.

This thesis considers the cumulative opportunity loss per unit time as discrepancy (deviation from the goal) and this variable is used to drive the model, i.e., to determine maintenance policy. The main objective is to minimize life-cycle cost, subjected to mission readiness. The main objective may also be to minimize opportunity loss.

2.3.4. General Failure and Maintenance Policies (Model)

Beichelt (1992) has presented a general model for a system. Any system has two types of failures: type 1, that can be removed by minimal repairs and type 2, which can be removed by replacements. Beichelt (1992) has considered both failure types. Minimal repairs do not alter the failure rate (memory less), but put the system back in operation. In case of replacements, the failure rate is altered. Beichelt's model has been solved for various policies mentioned below:

1. The system is maintained according to the failure type. In this policy, the cycle length (i.e. the time between successive replacements) is random and the expected number of type 1 failures is computed. This is the simplest of all policies;

2. The system is replaced at system age '*t*';

3. The system is replaced after *n-1* minimal repairs, i.e., at the *n* failure;

4. On failure, the system is replaced if the random repair cost exceeds a given repair cost limit;

5. In policy 4, in addition, there is a preventive replacement made at system age '*t*'.

2.3.5. Gama Approach for Maintenance Scheduling System

Park (1975) has developed a gamma approximation model to determine the minimum cost of preventive maintenance schedules when accurate failure data is not available except the mean and the mode of component lifetime. This model is particularly useful since it is usually difficult to get main data on maintenance, *i.e.*, data on the components lifetimes, probability distribution of lifetime, etc. From historical accounting data, we can calculate the average cost of scheduled preventive maintenance and the average cost of breakdowns, including costs of downtime and possible lost sales, idle direct and indirect labour, delays in dependent processes, increased scrap and cost of repairs.

When accurate data is not available, a Gamma distribution is considered to be useful since it only requires estimates of average and most likely (or mode) component lifetimes to describe the specific failure distribution. Also in case of the Gamma distribution, it captures increasing failure rates, which has been observed to be the case with most components.

This model has been shown to be robust against underlying lifetime distributions, i.e., with other distributions like the Weibull, and with respect to errors in estimating the mean and modal lifetime values.

Ntuen (1984) has also used a truncated gamma failure distribution. His hypothesis model is that an optimal maintenance policy should balance the failure cost of a system during operation against the cost of planned maintenance.

2.3.6. Simulation and Economic Analysis for the Selection of the Moment for Corrective Maintenance

Sheu and Krajewski (1994) have developed a decision making approach for corrective maintenance management. It consists of a simulation and is complemented by an economic analysis. The simulation model predicts the inventory costs and effectiveness of a corrective maintenance policy. The simulation results feed into an economic analysis, comprising a Net Present Worth (NPW) and breakeven analysis model that determines the economic worth of various maintenance policies. The authors have presented an example to evaluate the options of machine redundancy and worker flexibility. Machine redundancy refers to the use of standby machine or extra capacity in some other machine while worker flexibility refers to the number of operations each worker can perform. The benefits of worker flexibility include the use of cross trained workers that release the load at bottlenecks during machine breakdowns. The two forms of redundancy mentioned above need not be mutually exclusive, i.e., a combination of the two may be preferred. To analyse the economic worth of maintenance policies, the model requires information on:

a) The manufacturing performance of alternative maintenance policies regarding customer service (backlogs) and inventory cost that can be provided by a simulation model;

b) The costs of implementing each maintenance policy, e.g., the cost of cross training workers and the capital cost of machine redundancy. This information is then used to perform *NPW* calculations and breakeven analyses for the various maintenance options. In the given example, the author has carried out breakeven analyses to determine the effect of certain variables like the cost of capital and training costs. The model provides useful information for a manager in determining an effective maintenance schedule. The comparison of various maintenance policies is analogous to that of comparing project alternatives. According to the authors, the above model can be extended to preventive maintenance policy making. The research methodology of this thesis uses life-cycle cost along with opportunity loss as the metrics that determine optimum maintenance policy for a system. This model uses NPW and breakeven analysis for the same purpose. In the future, it may be worth using other metrics like a cost-benefit ratio to determine optimal preventive maintenance policies.

2.3.7. Other Models

Various other models have been developed using techniques like linear programming, non-linear programming, dynamic programming, mixed integer programming, decision theory, search techniques and heuristic approaches (Sherif, 1981). The following models are briefly described in this section to give to the reader information about other techniques used for maintenance modelling.

Hariga (1996) has developed a general model to determine a periodic inspection schedule as part of a preventive maintenance policy for a single machine subject to random failure.

The problem has been formulated as a profit maximization model with a general failure time distribution. A heuristic approach has been developed to obtain an approximate inspection schedule, when the failure times are exponentially distributed.

Menipaz (1974) introduced the concept of a discounting factor to bring all future cash expenses to time, t = 0. The objective function considered is the expected cost per cycle when some or all cost components are variables and a discount rate is assumed. The objective function is solved using a differentiation method and a dynamic programming approach.

Zuckerman (1986) developed a stochastic model to determine the optimal maintenance schedule under the following criteria: long run average cost and total expected discounted cost over an infinite horizon. The system is subject to shocks causing a random amount of damage to the system components. The research methodology uses the average opportunity loss as a driver to determine the maintenance policy.

Inozu and Karabakal (1994) have formulated a model that is marine industry specific. According to the authors, the maintenance schedule in the marine industry is very complicated owing to conflicting objectives. Here a new approach to perform group (multi-item) replacement has been proposed under budget constraints (capital rationing). It considers all replacement decisions of an entire ship fleet (or all component replacements for a single ship) simultaneously. The problem has been formulated as an integer linear program.

A Lagrangian methodology for the replacement problem is also presented. This has been introduced to find the dual of one of the constraints, namely, the capital rationing constraints, and incorporate it into the objective function in order to solve the integer program easily.

Sim and Endrenyi (Sim, 1988) have developed a minimal preventive maintenance model for repairable, continuously operating devices whose conditions deteriorate with time in service. This model is useful for devices like coal pulverisers, circuit breakers and transformers. The preventive maintenance times are assumed to have an Erlang distribution while the failures are Poisson distributed. Deterioration failures have been considered in the model. The objective function used by the model is to minimize the system unavailability.

Sherif (1982) has developed an optimal maintenance model for life-cycle costing analysis that determines a schedule that minimizes the system's future total expected maintenance cost. This may be added to other costs like acquisition, salvage and operation costs to obtain the life-cycle cost. The equations for optimal maintenance schedule and minimum expected future cost of the system, developed in the model, are solved recursively using dynamic programming principles.

2.3.8. Distribution for the Time Spent on Maintenance Operations

The normal distribution applies to relatively straightforward maintenance tasks and repair actions. The log-normal distribution applies to more sophisticated tasks where times and frequencies vary. Exponential and Poisson distributions apply to electronic components with sudden failures (Hoopes, 2003).

2.3.9. Metrics used in Maintenance

As the adage goes, you cannot improve a process without first measuring its performance (Bill Gates, 2014). But what are the most important maintenance metrics or Key Performance Indicators (KPI) you should measure?

By definition (Significados.com, 2015), KPIs facilitate the vision and mission of a particular company transmission process to the employees who do not occupy high positions. In this way, all employees of various hierarchical levels are involved in the mission to achieve the strategic targets set by the company. A key performance indicator serves as a communication vehicle, ensuring that employees understand how their jobs are important to the success or lack of success of the organization.

In the business world, the KPIs are quantifiable measures used to understand whether the company’s objectives are being met. Consequently, these indicators determine whether to take different attitudes to improve current results. Performance key indicators should only be changed if the primary objectives of a company also undergo change.

Establishing a baseline for success should be the first step whenever you set out to improve something. Bill Gates (2014) draws the example of the steam engine – one of the biggest advancements in the industrial age, as being a product of incremental design changes and precise feedback. “Without measurement,” writes William Rosen, invention is “doomed to be rare and erratic”.

With the steam engine, the criterion is fairly straightforward. A superior design would have some combination of being lighter, more powerful, more fuel efficient, cheaper to construct, etc.

The same is true for maintenance metrics and there is a wealth of performance indicators that can be used to measure and improve performance. For example (Figure 5):

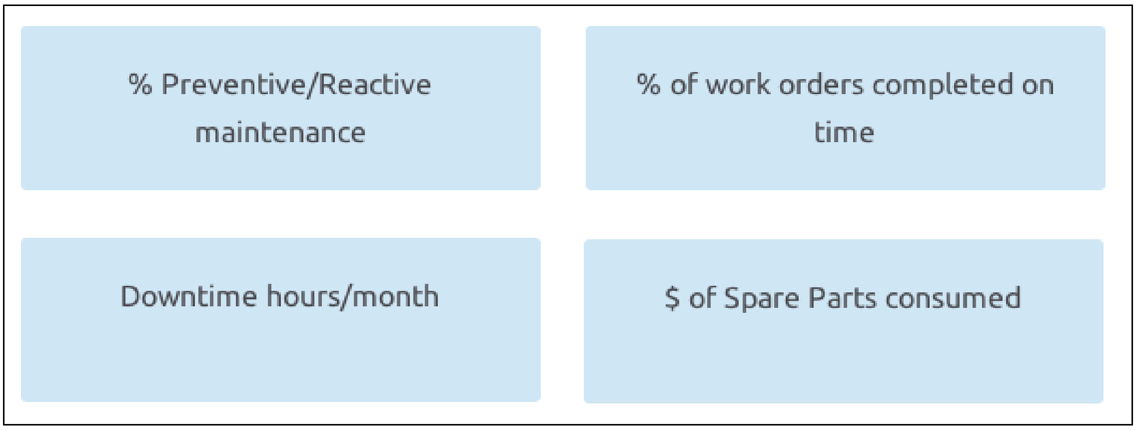

Figure 5 - Maintenance metrics example (http://www.mbaskool.com)

Minimizing downtime might seem like a worthy goal, but not if it also has a negative impact on product quality and employee morale, otherwise, it jeopardizes a longer term strategy of increasing the proportion of preventive/reactive maintenance. When optimizing the department, there are dozens of confounding factors to be considered. The struggle then becomes which maintenance metrics to focus on.

The balanced scorecard approach was first introduced in the early 1990's and encouraged managers to track performance using a variety of metrics. The central idea is to avoid optimizing one area at the expense of another. Increasing machine availability by stocking an excessive number of spare parts - OEE improves, but inventory costs skyrocket as well. The age-old practice of measuring performance based solely on financial indicators alone has been found to be inadequate and missing the whole picture. Hence, a new school of thought has emerged that reconciles high-level financial measures with more practical day-to-day indicators.

Balanced scorecards (Figure 6) provide a clear and effective approach to capturing a high-level view of the organization.

Critical Success Factor	Key Result Area	Key Performance Indicator
Financial Performance	• Cost • Revenue	Maintenance cost/unit* ROI (maintenance)
Customer Satisfaction	• Quality • Service	No. of complaints Value for money Referrals
Process Performance	• Equipment performance	OEE**
Employee/Environmental Safety	• Health • Safety • Legal requirements • Environment	No. of Accidents No. of HSE complaints Employee complaints

Table 1 Balanced Scorecard approach to maintenance management

Figure 6 - Balanced score card example (http://www.mbaskool.com)

**Cost/unit should be defined based on the organization specifics. Generally speaking, it will include some combination of labour, spare parts, overtime, contract labour, utilities, insurance, etc.*

***OEE: Operational Equipment Effectiveness = (Availability)*(Performance)*(Quality)*

This holistic approach to maintenance brings the organization one step closer to integrating maintenance with other high-level goals, and promotes the idea that maintenance should be viewed as an input to production instead of a necessary waste.

2.4. Lifecycle Cost Concept

The life-cycle cost (also referred to as "ownership cost") may be defined as the total cost of a system or product to be incurred over its anticipated useful life in research and development, construction, production, operation, maintenance and support, retirement and disposal. It is the total cost of a system ownership. This is not a new concept, but it is an updated version of the capitalized cost analysis that uses Nissan Production Way (NPW) to evaluate a system (Ntuen, 1984). Lifecycle Cost Concept (LCC) problems are quite complicated and hence can be considered as a computational technique for studying design and operational alternatives (Ntuen, 1984). In general, LCC is the sum of acquisition cost (which is the sum of purchase, Research and development (R&D), commissioning costs), the present worth of annual maintenance cost over the intended period of service, the disposal cost and all the other costs expected to be incurred discounted to the present time.

The life cycle cost is considered during the analysis of alternatives (AoA) since decisions made early in the system life cycle have significant cost impact downstream, i.e., in the future. There is a need to extend planning and decision-making to address system requirements from a total life-cycle perspective.

The use of the LCC can influence system design and assist in producing low cost systems. For existing systems, it can form the basis of a continuous improvement process. In both cases, the LCC creates awareness among the designers to produce an effective system with not only a low acquisition cost but also low operation, support and disposal costs. LCC models vary in scope and form.

There is no standard LCC model. Most of the models developed are case-specific rather than universal (Sherif, 1982). From a management standpoint, LCC is an integral part of the ultimate goal to achieve desired system performance (and readiness) at an affordable cost. The desired level may be subjective or objective. In the model developed in the next chapter, the life-cycle cost is calculated to determine the effectiveness of various maintenance policies.

2.4.1. First Steps in the Lifecycle Cost Analysis

The basic steps involving a lifecycle cost analysis are:

1. Describe the system configuration being evaluated in functional terms and identify the appropriate technical performance measures or applicable "metrics" for the system;

2. Describe the system life cycle and identify the major activities in each phase as applicable (e.g., system design and development, construction/ production, utilization, maintenance and support, retirement/ disposal);

3. Develop a work breakdown structure (WBS) or cost breakdown structure (CBS), covering all activities and work packages throughout the life cycle. The work breakdown structure involves a breakdown of all the necessary activities involved throughout the life-cycle. Cost breakdown structure involves the following:

   (i) Includes all costs direct, indirect, supplier, consumer, contractor, etc.;

(ii) Provides insight to management regarding design and decision making;

(iii) A structure for initial cost allocation and the subsequent collection and summarization of costs;

(iv) Complete description of cost categories, cost determination methods and cost input factors;

(v) A functional breakdown of costs (i.e., costs of R&D, production, operations and disposal).

The cost breakdown structure must be tailored for each system application.

4. Estimate the appropriate costs for each category in the cost or work breakdown structure, using activity-based costing (ABC) methods (Canada, 1996), or the equivalent. Activity-based costing gives a more accurate cost since it does not apportion the overhead on a company-wide basis, instead activity costs are directly linked to the product or system that causes it;

5. Develop a model to facilitate the life-cycle cost analysis process. Considering the complexities involved, it may be advisable to develop a computer-based model;

6. Develop a cost profile for the "baseline" system configuration being evaluated. The initial cost estimated becomes the baseline and other configurations are compared to this baseline;

7. Develop a cost summary, identifying the high cost contributors (i.e. high-cost "drivers");

8. Determine the "cause-and-effect" relationships and identify the causes for the high cost areas;

9. Perform a sensitivity analysis to determine the effects of input factors on the results, and identify the high-risk areas or areas that could lead to substantial increases in cost;

10. Draw a Pareto diagram, which is a non-increasing order of the relative importance ranking for major problem areas. Rank the high-cost areas in terms of their relative importance that require immediate management attention;

11. Identify feasible alternatives (potential areas for improvement), perform a life-cycle cost profile (graph of annual cost) for each, and carry out a breakeven analysis showing the point in time when a given alternative assumes a point of preference;

12. Recommend a preferred approach and develop a plan for system modification and improvement (equipment or software or process). This constitutes an on-going iterative approach for continuous process improvement.

The model developed in this thesis involves steps 1 through 5. The steps 6 through 12 are also essential and may be used in conjunction with the model by the decision-maker.

2.4.2. Lifecycle Cost Analisys Aplication

Applications of the life-cycle cost concept has taken place in various areas like evaluating alternative supplier proposals, design configurations, production profiles, logistics and maintenance support policies, identification of high-risk contributors (issues that are expected to have a significant effect on the life-cycle cost of the system), long-range budgeting and allocation of resources, project management and control, and replacement policies of existing systems.

In the “alternatives identification” stage, LCC may be used to compare alternatives using simple parametric Cost Estimating Relationships (CER). After selecting a particular configuration or system, design trade-offs may be evaluated based on LCC calculations.

After construction of the system, LCC may be used for engineering change evaluations using more detailed analytical CERs.

When the concept of LCC is applied to new systems, then it could influence design for lower life-cycle cost. When it is applied to existing systems, then it could be used to assist the "continuous improvement process" to lower life-cycle cost, and redesign of costly items, policies and other tactical decisions.

2.4.3. Benefits of Lifecycle Cost Analisys

There are various benefits life-cycle costing (Ntuen, 1984). Some of them are:

1. Fosters long-range considerations and helps avoid myopic or short-term decisions;

2. Necessitates total cost visibility;

3. Establishes relationships between different system components and elements of cost;

4. Causes a reduction in risk by identifying potential "high-risk" areas;

5. Allows for better overall resource management;

As mentioned earlier, the research methodology of chapter 3 uses the life-cycle cost as a metric, along with opportunity loss, to determine an optimum maintenance policy.

2.5. Maintenance Costs

Maintenance costs are, in most cases, taken by the various companies management groups as those costs that, by not indicating direct incomes, as usually the most difficult to justify and, in some cases, more difficult to ensure.

Hence, below are the definitions of the different maintenance costs associated, interpreted according to a "theoretical" point of view and then compared with reality in an industrial environment.

2.5.1. Preventive Maintenance Costs

Multi-objective preventive maintenance optimization models have been presented in several papers. Kralj and Petrovic (1995) present a novel approach in preventive maintenance scheduling of thermal generating systems. The authors developed a large-scale multi-objective combinatorial optimization model with three objective functions and a set of constraints. They consider minimization of total fuel costs, maximization of reliability in terms of expected unnerved energy and minimization of technological concerns as the objective functions. In addition, they defined maintenance duration, maintenance continuity, maintenance season, maintenance sequences of same class thermal units, limitation on thermal units' simultaneous maintenance, and limitation on total capacity on maintenance due to labor and resources as the constraints. They developed a multi-objective preventive maintenance scheduling software based on a multi-objective branch and bound algorithm implemented in FORTRAN. Finally, the researchers apply their methodology to a real system of eight power plants with twenty one thermal units and eleven maintenance classes over thirty three weeks as the planning horizon.

Chareonsuk *et al* (1997) developed a multi-criteria preventive maintenance optimization model to find the optimal preventive maintenance intervals of components in a production system. In this study, the authors consider an age-based failure rate for components by fitting a Weibull distribution to the data and define expected total cost per unit time and the reliability of the production system as the main criteria. Following, they utilized a preference ranking organization method for enrichment evaluations (PROMETHEE) as the solution approach and defined the alternative decisions as the preventive maintenance intervals. By using this approach, they can aggregate preferences of alternatives by combining the weighted values for the preference functions of the criteria complete set. As a case study, they apply their methodology in a paper factory and used PROMCALC as the optimization software. Finally, they mention the advantage of their approach in which decision makers and managers can input various criteria into the model and do sensitivity analysis on the optimal solutions.

Konak (2006) presented a comprehensive study on multi-objective genetic algorithms and their applications in reliability optimization problems. They review fifty five research papers and talks about the recent techniques and methodologies.

Quan (2007) developed a novel multi-objective genetic algorithm in order to optimize seventeen preventive maintenance schedule problems. They defined the problem as a multi-objective optimization problem by considering the minimization of workforce idle time and the minimization of maintenance time and mention that there is a trade-off between the objective functions. As the solution procedure, they used utility theory instead of dominance-based Pareto search to determine the non-inferior solutions and show the advantage of this method via numerical example.

Taboada (2008) present a recent study in this area. They developed a multi-objective genetic algorithm in order to solve multi-state reliability design problems. The authors utilized the universal moment generating function to measure the reliability and availability criteria in the system. They applied their approach into two examples; the first one is a system of five units connected in series in which each component has two states, functioning properly, or failure and the second one is a system of three units connected in series. In this system, each component has multi-states with different levels of performance, which range from maximum capacity to total failure. They utilized MATLAB as the programming environment, and shown the effectiveness of their approach in terms of computational times and obtained non-inferior solutions.

All of this approaches resulted in substantial reductions concerning Maintenance Costs. Despite the different theoretical basis, the survey of all the factors, their study and application in a concerted way resulted on the knowledge and quantification thereof upon failure analysis and consequently the anticipation of possible unnecessary costs.

2.5.1.1. Failure Costs

When a failure incident occurs there is a consequent loss of profits (Sondalini, 2006).

The cost of failure includes lost profit, the repair cost, the fixed and variable operating costs wasted during the downtime and a myriad of consequent costs that reverberate and surge through the business. These are all paid by the organization and seen as poor financial performance.

The costs of failure cannot be escaped and are counted in millions of euro of lost profit per year. Total defect and failure true costs are not normally recognized by managers, yet they can send businesses bankrupt. In the instance of a failure all its costs and losses are automatically incurred on the business. These costs can only be prevented by precluding the failure in the first place.

Every business has fixed costs (Figure 7) that it must carry on regardless of how much it produces. These include the cost of building rent, the manager's salary, the permanent staff and employees' wages, insurances, equipment leases, etc. There are variable costs as well, such as fuel, power, hire labour, raw materials to make product, etc.

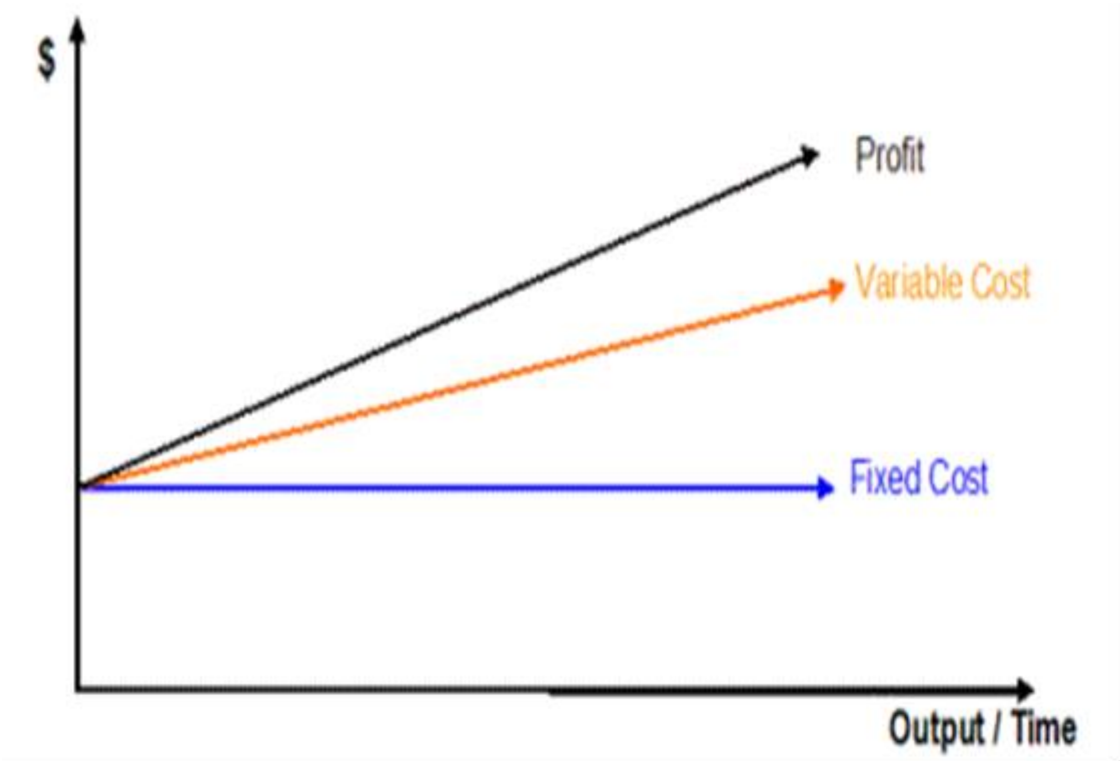

Figure 7 - Usual business operation (www.bin95.com)

We can take the same analogy of normal business operation down to normal equipment operation. When plant and equipment are running each item has a fixed cost, a variable cost and generates a contribution to the overall business profit. It is reasonable to look at every machine and item of plant in your operation as contributing their share to the total profit of the business - their 'profit contribution'. When one of these items cannot be used for production it cannot contribute to profit. If the reason of the non-operation is because it has failed, then it is not contributing to profit performance and it also imposes added costs on the business (Figure 8).

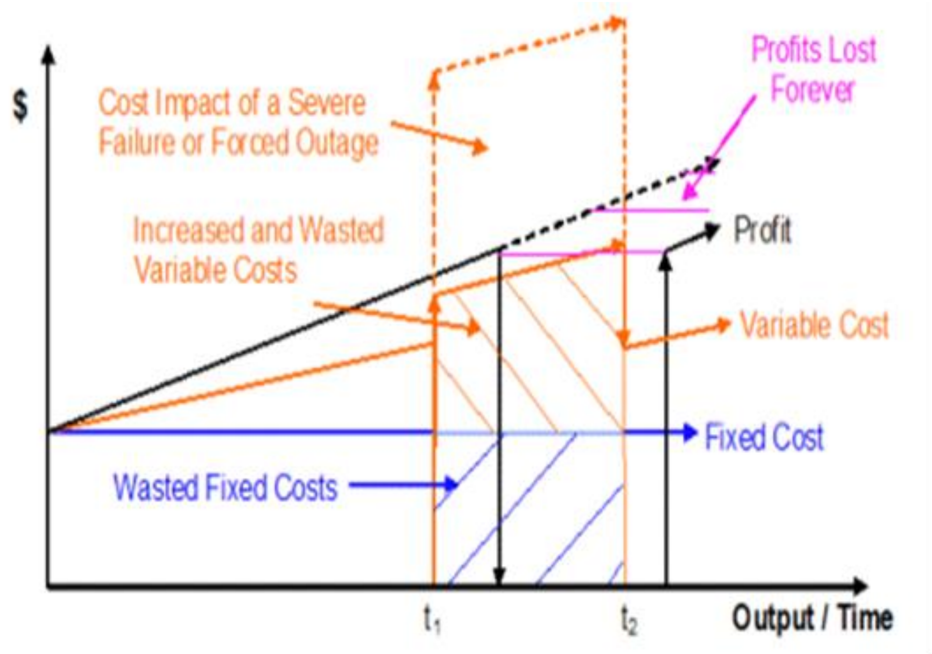

Figure 8 - Effects on costs and profit of a failure incidente (www.bin95.com)

When a failure happens, many people suddenly get involved in solving it. Meetings are held, overtime is worked, subcontractors are brought-in, engineers investigate and parts and spares are purchased to get back in operation. Instead of the variable costs being a proportion of production, as intended, they rise and take on a life of their own in response to the failure. The losses grow up proportionally bigger the longer the repair takes or the greater the consequences of the failure exist.

The costs keep on growing, more and more people throughout the company waste time because of the failure, during larger periods of time.

The company pays for all of it from its profits, which is then reflected in poor financial performance. The reactive costs and the resulting wastes start immediately upon failure and continue until the last cent is paid on the final invoice.

2.5.1.2. Maintenance Costs

One universal measurement of maintenance performance, and perhaps the measure that matters most in the end, is the cost of maintenance. Regrettably maintenance costs are often used to compare maintenance performance between companies or between plants within the same company (Idcon, 2015).

Equally unfortunately, there is no standard for measuring maintenance costs. Each company, usually each plant within a company and often each department within a plant develop their own definition of "maintenance costs."

For this reason, maintenance cost comparisons should always be accompanied by a clear definition of what is included and excluded for each plant contained in the comparison, for which, one can find the figure show bellow very helpful (Figure 9):

Type of cost (materials and labor)	Recommended cost category
Preventive maintenance	Maintenance
Corrective maintenance (repair or replacement of failed components)	Maintenance (unless its a capital replacement)
Lubrication (a specific PM task)	Maintenance (In some plants this is a Production cost)
Contracted preventive and corrective maintenance	Maintenance
"Maintenance" work done by Production employees. This can included cleaning, inspections, replacement of "production" components (e.g. filter media, etc) and perhaps some lubrication.	Production - but remember to take these costs into account when making comparisons
"Non-working" maintenance labor (e.g. maintenance safety meetings, waiting time, etc)	Maintenance
Maintenance supervision, planning and administration	Maintenance
Non-capital plant improvements. This includes both process and reliability improvements	Probably maintenance, however its a good idea to include an "improvement" category in Work Order codes to allow improvement costs to be identified
Capital improvements and replacements	Capital (but remember that the definition of "capital" also varies widely)
Disposal of obsolete and surplus stock and inventory adjustments (where inventory is working capital)	A special expense account, separate from other costs and not in the maintenance budget

Figure 9 - Maintenance cost comparison table example (http://www.mbaskool.com).

Once again, in a “practical” point of view, these costs are analysed by comparing the effective cost in maintaining equipment with its real participation in the final production level. Using Continental company as an example, a cost (whatever that may be: scrap, maintenance, etc.) is always compared according with the daily global tire production.

2.5.1.3. Replacement Costs

Using Continental as an example, we can conclude that the cost of replacing equipment is always analysed by the needed time for start providing the expected revenues.

Thus, sometimes, some particular equipment has to be replaced for safety or ergonomic issues, those are the only situations when the replacement of equipment is not analysed or decided purely by the financial way.

2.5.1.4. Overhead Costs

For a multi-component system, and the cost structure defined above, the problem can be solved as a problem of finding the optimal sequence of maintenance, replacement, or do-nothing actions for each component, independent of all other components. Thus, one could simply find the best sequence of actions for component 1 regardless the actions taken to component 2 and so on. This would result in *N* independent optimization problems. Such model seems unrealistic, as there should be some overall system cost penalty when an action is taken on any component in the system. It would seem that there should be some logical advantage to combining maintenance and replacement actions, e.g., while the system is shut down to replace one component, it may make sense to go ahead and perform maintenance/replacement of some other component, even if it is not at its individual optimum point where maintenance or replacement would ordinarily be performed.

Under this scenario, the optimal time to perform maintenance/replacement actions on individual components is dependent upon the decision made for other components. As such, it was proposed that a fixed cost of “downtime” should be charged in period if any component (one or more) is maintained or replaced in that period.

Consideration of this fixed cost makes the problem much more interesting, and more difficult to solve, as the optimal sequence of actions must be determined simultaneously for all components.

2.5.1.5. Total Costs

According to Reibstein (2010) in economics and cost accounting, Total Cost (TC) describes the total economic cost of production and is made up of variable costs according to the quantity of a good produced and include inputs such as labour and raw materials, plus fixed costs, which are independent of the good quantity produced and include inputs (capital) that cannot be varied in the short term, such as buildings and machinery.

Total cost in economics includes the total opportunity cost of each production factor as part of its fixed or variable costs.

The rate at which total cost changes as the amount produced changes is called marginal cost. This is also known as the marginal unit variable cost.

If one assumes that the unit variable cost is constant, as in cost-volume-profit analysis developed and used in cost accounting by the accountants, then total cost is linear in volume, and given by:

$$\text{Total Cost} = \text{Fixed Costs} + \text{Unit Variable Cost} \times \text{Amount} \quad (1)$$

Adapting this definition to Continental Mabor, is clear the direct association of some costs to the equation represented above.

We can then consider as fixed maintenance costs the ones associated with employees (maintenance teams) and components whose consumption we know in advance.

As variable costs we can consider the ones concerning overtime and material needed for unplanned interventions/operations, tools (other than those of wear) and possible subcontractors work.

3. Development

3.1. Objectives

The present work aims to demonstrate the importance and added value represented by the integration of the "project team" figure in the already widely known maintenance process, which included the Breakdown/Curative, Preventive and Predictive/Conditioned maintenance teams. With this integration is aimed nothing more than to reduce the intervention cycle on a machine from the time it is requested by an intervention for breakdown reasons but also, and at the same time, ensure the installation of new equipments, support for day-to-day production processes on equipment upgrade in the shop floor, to ensure new productive processes and/or security updates and layout settings.

The main objective of this dissertation is therefore to confirm the relevance of such integration in the final results of the Engineering Department in the lost times, maintenance costs and OEE. In order to prove the effectiveness of this system, it will be described the intervention carried out in a textile fabric cutting machine, which, by their design, age and rate of utilization, was a real Achilles heel of the Department as a result of time lost through malfunction and starting difficulties whenever there was a longer stop or after a few hours break period for preventive maintenance. This equipment became a perfect example to demonstrate the effectiveness of the theory proposed since, as a result of lost time and scrap generated by failure, synchronization issues when running automatically and difficulty in adapting to new processes and / or products, was the subject of many brainstorms developed between engineering teams and other departments involved in the manufacture process, culminating in certainty as to the need for concerted action conducted by the Projects team.

Thus, a specification was drawn up by the project team, perfectly integrated in the maintenance process, after meeting with teams of Preventive, Curative and Production (in order to address some difficulties in the processes, due to the equipment age and to ensure some features perceived as necessary for the processing of materials that, in future, will enter the production planning) the necessary work was put out to tender, awarded to a supplier, executed, approved by quality and production and, currently, the indicators presented speak for themselves.

3.2. Company Characterization

Continental Group

Continental was founded in Hanover, Germany, in October 1871.

Originally, the company was focused on manufacturing flexible rubber artifacts and solid tires for carriages and bicycles. In 1898, it started to produce flat tires (no tread design) for automobiles. Since then, it has followed the evolution operated in the automotive industry with the application of techniques, products and equipment for the improvement of tires and their manufacturing processes.

Your reputation goes beyond the Germany borders and Continental tires started to equip winning cars in various car competitions.

With a highly diversified production, Continental AG Group has its sales volume centered on tires of various sub-brands for passenger cars, light trucks, agricultural, industrial equipments and motorcycle integrated into Tire Division.

The Group is also composed of the Systems Division for the Automotive Industry, which is part of the braking systems manufacture, electronic components and systems for light and heavy vehicles. This Division is responsible for developing of automotive systems such as Anti-lock Braking Systems (ABS), Electronic Stability Control (ESP), Traction Control Systems (TCS), Electronic Suspension Systems (EES), among others.

ContiTech is another division of the Rubber Group which manufactures industrial products based on rubber intended for mining industry, printing, furniture and machinery manufacturing.

Continental, with its estimated 150.000.000 tires per year global production, is currently the first tire producer in Germany, the second at European level and the fourth worldwide. One in every four vehicles produced in Europe are equipped with Continental tires.

Continental AG has several tire plants as well as technology development centers and test tracks spread across several continents (European, American, Asian and African), and consists of a workforce of more than 170.000 employees around the world.

The Continental Group Worldwide

Currently, the Continental universe consists of 269 production units, research and development in 46 countries spread over 5 business areas throughout the world.

Continental Group in Portugal

In Portugal, the Continental Corporation is made up of five companies: Continental Mabor, Continental Pneus, Indústria Têxtil do Ave, Continental Teves and Continental Lemmerz.
Together, they represent a workforce of more than 2000 employees.

Continental Mabor, Indústria de Pneus S.A. (CMIP)

Foundation Year: 1989

Location: Lousado, V. N. Famalicão

Products: Passengers and Light Trucks Tires (PLT)

History: Resulted from the fusion between Mabor (Manufatura Nacional de Borracha, S.A.) and Continental Group.

Figure 10 - Continental-Mabor plant

Continental Pneus (Portugal) S.A. (CPP)

Foundation Year: 1992

Location: Lousado, V. N. Famalicão

Products: Marketing in Portugal, the tires produced by Continental AG

History: This company was constituted through the acquisition of all shares of Scrimex (which owned the marketing exclusivity for Continental tires brand in Portugal). The ContiPneus integrated the transferred employees from Scrimex and also from Mabor and started selling Continental products, among others sells Continental, Semperit, Uniroyal and Mabor tires.

Figure 11 - Continental-Pneus facilities

Indústria Têxtil do Ave, S.A. (ITA)

Foundation Year: 1950

Location: Lousado, V. N. Famalicão

Products: Textile products for the rubber industry

History: It belonged to the same group that held Mabor (Amorim Group). Became part of the Continental Group AG in 1993
.

Figure 12 - ITA plant

Continental Lemmerz (Portugal) - Componentes para Automóveis, Lda. (CLCA)

Foundation Year: 1994

Location: Palmela, Setúbal

Products: Automotive Components

History: It was established as a "joint venture" with the purpose of ensuring the tire-wheel assemblies just-in-time to Auto-Europa Volkswagen plant. 51% of the Company's capital is held by Continental Mabor and the remaining 49% by Schedl.

Figure 13 - Continental-Lemmerz plant

Continental Teves – Sistemas de Travagem, Lda.

Foundation Year: 1998

Location: Palmela, Setúbal

Products: Braking Systems

History: This plant manufactures and assembles brakes for major car manufacturers in Europe. Currently has an installed capacity of about 4 million brakes per year.

Figure 14 - Continental-Teves plant

Continental Mabor

Figure 15 - Continental Mabor, plant global perspective

Location

Located at Famalicão (Figure 15) county southern end, Lousado has in Santo Tirso and the right bank of Ave's river its limits. Lousado's main economic activities are the general trade and textile, tires, clothes manufacturing, metallurgy, aluminium and plastics transformation, as well as small-scale farming.

History

The Continental Mabor was born in December 1989 (Figure 16). Its name comes from the union of two renowned companies in the tire manufacture, Mabor, nationally, and Continental AG. of a global dimension.

Figure 16 - Mabor old facilities

Mabor – Manufatura Nacional de Borracha, S.A., was the first tire factory in Portugal, having begun working in 1946 under technical assistance of the General Tire C.ª, from Ohio, United States of America (U.S.A.).

July 1990 saw the start of the major restructuring program that has transformed the old Mabor facilities in the most modern of then 21 Continental units. Starting in 1990 with a daily average production of 5.000 tires, in 1996 the 21.000 tires per day barrier have been broken, it means that production level had quadrupled. Initially producing only the Mabor brand tires, the range of the company is currently very varied either in articles, types or brands, comprising Continental, Uniroyal (Europe), General Tire, Semperit, Gislaved, Viking, Mabor and Barum as commercialized brands.

There is also the production of high tech tires like the ones specially developed for excellent performance at high speeds, winter tires, and ecological tires - once they are developed in a way that reduces the vehicle fuel consumption. Continental Mabor includes also in its portfolio tires designed for SUV’s and recently started the 21 inches wheel tires production. It also produces ContiSeal (anti-hole technology), ContiSilent (low noise levels) and just started with the Ultra Ultra High Performance (UUHP) tires production.

More than 98% of its production is focused on external market, mainly, distributed by the assembly lines of the most prestigious automotive manufacturers. The designated “replacement market” correspond to 60% of Continental Mabor annual production.

Manufacturing Process

The Continental Mabor manufacturing process is divided into five main parts, assured by six departments, which correspond to the different stages of the tires manufacturing processes.
Following, it will be provided some information about the activity of each department (Figure 17).

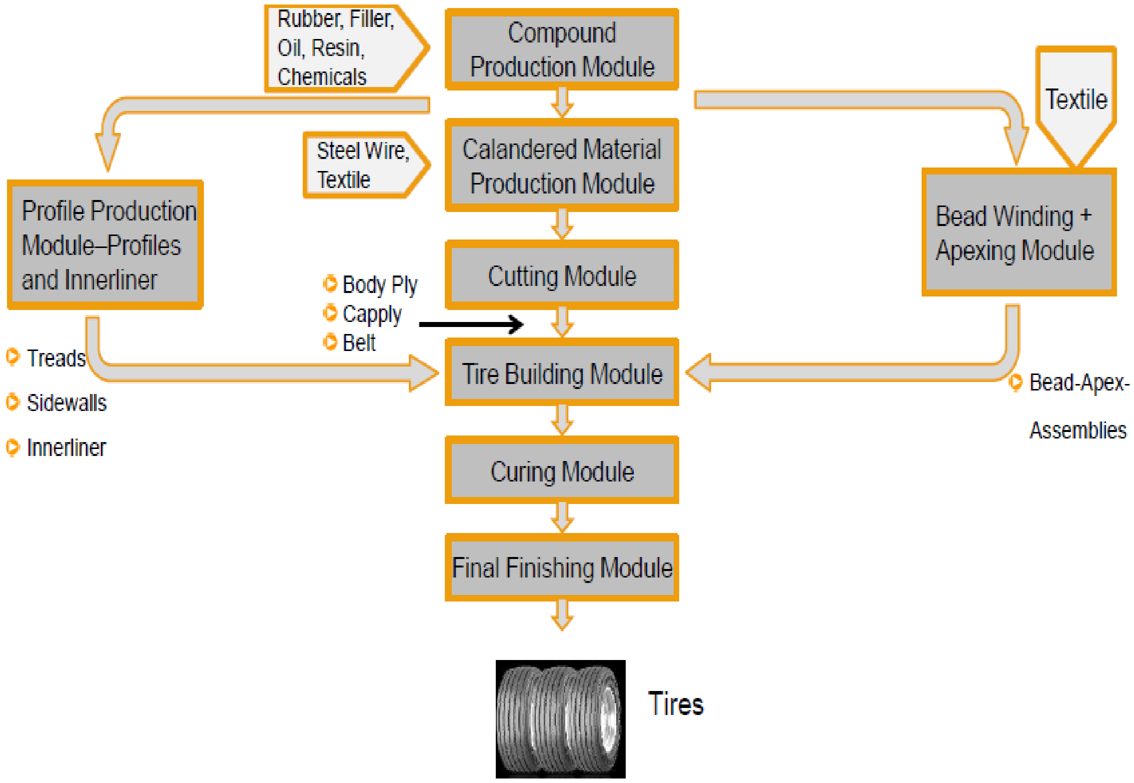

Figure 17 – Tire manufacturing process

Production Department I – Mixing

This department comprises the beginning of the production process, where are mixed all the compounds (natural and synthetic rubber, pigments, mineral oil, silica, carbon black, etc.) so that, after passing through the "masters" and "final" stages (two different kinds of rubber, the “master” is the one that can be used lately in other compounds, the “final” is the final compound that will be used in the production process), the rubber or compound (how it is named in the production process) can move to the following stage.

Production Department II – Stock Preparation Hot and Cold

In this department are made the beads and apexes, textile and metal plies, as well as the tire tread and side-walls.

Extruders, calendars and cutting machines are responsible for preparing these materials, whose will follow later through electrical transport trucks to the tire building area.

Production Department III – Tire Building

All the manufactured products in the previous steps are here assembled, resulting in the "green tire", also so-called pre-cured tire.

This assembly process is assured by the tire building modules, whose are constituted by two elements / machines, the construction machine (KM) machine that builds the carcass, and the Production Unit (PU) machine, responsible for the breaker assemble, tread and cap ply and then, finally, the complete set with the carcass made in the KM.

Production Department IV – Curing

At this stage, the tire is submitted to a process of high pressure levels (16 bar) and temperature (170°C) in the curing presses, where the mould will give the final appearance to the tire.

Production Department V – Final Inspection

All checks are made to ensure the whole tire quality requirements. This inspection process includes balancing and uniformity tests, X-Rays analysis and, finally, visual inspection done by experienced operators. Please pay attention that 100% of Continental Mabor's production is inspected before storage in order to ensure top quality level to our final customers. After this stage the tires follow to the finished product warehouse.

3.3. Evolution of the Maintenance Role in the Company

In a company as old as Continental Mabor, we can easily understand the changing role of maintenance fairly clear, being, in this case, quite noticeably the two completely distinct areas, Mabor and Continental Mabor.

Indeed, the inclusion of Mabor in the Continental group, among other issues, provided the company with new approach methodologies and methods to production processes and, more specifically, to the inherent maintenance processes.

The maintenance began to be seen as a need and assumed a key role in the constant demand for increased production, quality and product wise complexity.

It was assumed the importance of an available and with high levels of productivity and reliability industrial park, in order to achieve the proposed objectives regarding the company's core business, which is the tire manufacture in quantity, high quality level and under well controlled technical specifications.

3.3.1. Past Maintenance Management System Characterization

Before the Mabor integration in the *Continental* group, maintenance was practically reduced to Curative Maintenance, It means interventions in case of failure. Prevention was not a priority and reduced itself to small and temporarily distributed actions, without any rigor in the timely delivery of the concerned equipment's.

The preventive measures were part of a small checklist which was not properly controlled. There was no maintenance plans for each equipment individually and the maintenance actions were not structured. The period assigned to the preventive maintenance was, mostly, a chance to carry out cleaning and lubrication of the plant equipments.

Only since the mid-90s, with the development of a software called PEMS (Plant Engineering Maintenance System) that, slowly, began the mentality changing work and paradigms raise regarding this issue that, until then, was underappreciated, the preventive maintenance.

From then on, intervention plans began to be drowned up, data for further analysis were introduced in dedicated software (PEMS – Plant Engineering Maintenance System) and, above all, conclusions regarding actual or possible failures were reached based on facts.

This systematization was crucial to the development and subsequent growth of preventive action, allowing the enforcement of machines shutdown for preventive maintenance based on figures / real facts. This was undoubtedly a deciding factor in changing the preventive maintenance role within the company.

3.3.2. Reasons that have led to a New Approach to Maintenance

The need to increase the production levels, the increasing complexity of the final product and increased quality requirements during the manufacturing process and, ultimately, in the final product, were in the last analysis, the key factors for the increasing demand in terms of the industrial plant management.

The extension of the machines lifetime, continuous adaptation to new premises, the need for reliability and productivity levels never seen before and which became mandatory in order to assure a rapid integration into a multi-national group, all these aspects seemed impossible with the “traditional” maintenance management used until then.

Regarding this goal, it was required the reorganization of the engineering department, its sub-division into various departments specialized in support of the different production areas and, most of all, a revolution was needed in terms of attitudes and methods, not only at the engineering department level and their maintenance methods, but also in the production department, with the internal acceptance of the fact that without the completion of a strict maintenance plant, it is not possible ensure high levels of production stably .

Thus, before the integration in the *Continental* group, a maintenance system which cornerstone was the curative maintenance prevailed, troubleshooting, reaction, where prevention was limited only to carrying out cleaning and lubrication actions, the fulfilment of small checklists that did not meet any timescale, i.e. machines were being delivered upon the production department availability.

As the years went by and production capacity increased, this dysfunctional mind set has also evolved, gradually growing to a planned and structured maintenance. This new concept has been validated by the increasing availability levels of the equipment’s (OEE), by the decrease in breakdown downtime and scrap levels generated by incompatibility and/or machine malfunction, that is, all this new approach has been validated by the most important of all indicators for a company, the production volume and financial profits.

3.3.3. Present Maintenance Management System

In broad terms, the Continental Mabor Engineering Department is divided into five separate divisions (Figure 18) for the shop floor support but in unison regarding the application of good practices and supporting the production department concerns.

Thus, and as we can see in the organizational chart of the Engineering Department, directly linked to the industrial park we have:

- Engineering 1 allocated to the Mixing department, Extrusion and Calendaring;
- Engineering 2 responsible for Cold Preparation, Tire Building, Green Tire Transport System and Spraying;
- Engineering 3, responsible for Curing, Final Inspection and Conti Seal.

At the same time we also have the Infrastructure, Energy and the Expansion Projects Division, as the names suggest, deal with matters related to building, water supply, electricity, steam and HVAC (Heating, Ventilation and Air Conditioned), the last of which was recently created to deal with successive expansion projects that have took place in the company and which, by their complexity and need for detail, were consuming valuable and critical resources to other divisions in the daily assistance to the manufacturing process.

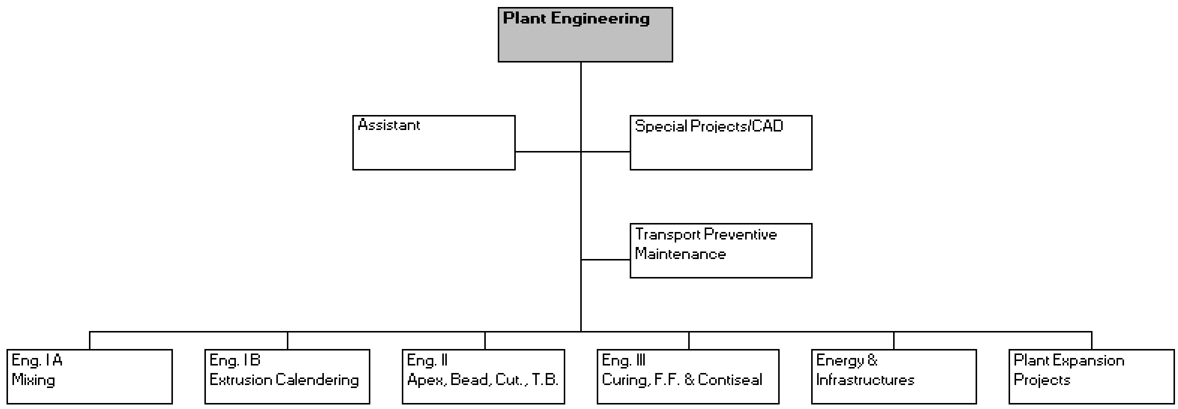

Figure 18 - Engineering department organizational chart

As previously explained, the equipment used as an example in the argumentation of the concept in study is a textile cutting equipment, being part of the Cold Preparation department which, by itself, is under the Engineering 2 (Figure 19) support and control.

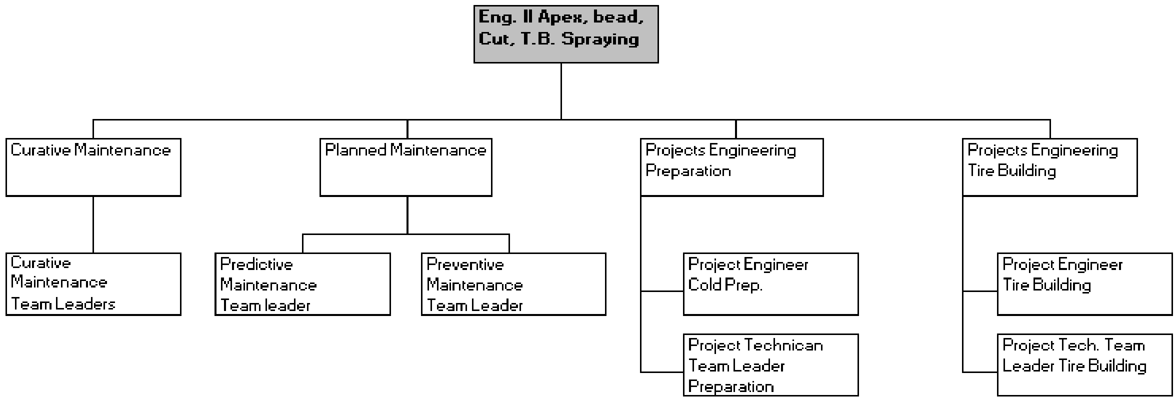

Figure 19 – Engineering II organizational chart

Just like the other Engineering Divisions, also this is divided into three teams, Planned (responsible for the management of Predictive/Conditional and Preventive maintenance teams), Curative maintenance and Projects teams.

3.3.4. Benefits and Limitations of the Current Maintenance Management System

At technical level, the maintenance system “on site” is reflected in numerous advantages, among them the following ones:

- Controlled Breakdown Time: the co-existence of multidisciplinary teams in the analysis and resolution of day-to-day problems allows greater control of lost time due to breakdown and hence the forecast of increasingly lower values for the future;

- Root causes of the failures quickly and efficiently identified: the advantages listed in the previous paragraph also mean that, on the occurrence of a malfunction, the discussion among the different department teams can, quickly and effectively, determine the root cause and quickly develop intervention or, at least, contingency plans / actions;

- Possibility for drawing up systematic action plans: action plans tailored to preventive maintenance and project teams as well as procedures and best practices for teams of curative maintenance are carried out in a systematic way and based on evidence gathered on the shop floor;

- Controlled Spare Parts Costs: by systematising to the most the interventions and optimize the teams capacity in proper diagnosis and fault repair procedures, we ensure a tight control in maintenance costs relatively to the spare parts;

- Controlled spare parts inventory: the number of spares in stock is directly related to the needs highlighted by the different teams, so the control carried out to the breakdown / failures incurred and their root causes allow us to have an accurate and updated idea, quickly and periodically, about the materials whose presence is required in storage and, thereby, ensure storage of the least possible amount of obsolete and unnecessary material;

- Existing and updated breakdowns history: this is undoubtedly one of the greatest advantages of the presented maintenance model, the ability in report and registers all the breakdowns and interventions occurred in the shop floor. Here, the use of digital platforms, such as the example the SAP management software that allows us to assign each department their machines on an individual basis and at the same machines, the different systems / circuits and components, all of them properly referenced and quoted;

- Effective and multi-purpose maintenance teams: the segmentation of the Engineering Department in support divisions to the different stages of the process allows a greater team specialization, translating into a fast breakdown diagnosis and solution, as well as the development of Planned Maintenance, with high levels of effectiveness.

These benefits or capital gains are reflected, in terms of output, in high levels of production and equipment availability (OEE) and, regarding the final product, reference quality levels within the Continental group. As limitations, it could be referred the lack of operational resources to analyse and transform into actions all the information collected through the intervention of the whole teams in the field, which can be a problem.

As a solution, it would be necessary to have a structure at the human resources level, which by itself would make its implementation difficult due to the higher costs involved, ie, the gains obtained through the use of this model could be overshadowed by the cost associated with its own structure. This can be, probably**,** the subject of study for another thesis.

3.4. Case Study

Inserted in the Cold Preparation department, the textile cutter machine #2 was, until the major upgrade, a hybrid in the sense that it was composed of two areas from the responsibility of two different suppliers, which in turn, implemented distinct software and control systems.

Essentially, this machine processes the calendared textile as follows:

1. The calendared textile roll, impregnated with rubber in the calendar, is placed in the textile cutter let-off;
2. The textile is then transported through a buffer and feeding conveyor until the cutting blade;
3. In the cutting blade (guillotine or roller blade), the fabric will be cut in straps with the needed width regarding the article (tire) specification. Here ends the cutting area;
4. Then, already in the tire construction zone, the cut straps are joined in the stitching area, forming a continuous line;
5. Finally, this continuous line is winded up with a pre-defined length in a cassette that, later on in the production process, will feed the Tire Building Machines (TBM) for the carcass construction.

Thus, the machine wherein the cutting area (let-off, feeding conveyor and guillotine) was a Fischer product (Karl Eugen Fischer GmbH - Maschinenfabrik) equipped with Siemens S5 control, as opposed to the construction zone (suction bar, splicing table and wind-up), supplied by Conti Machinery (CM) with Beckhoff control.

This condition resulted in a huge problem due to the time lost in fault diagnosis and resolution, set-ups and start-ups after prolonged maintenance or breakdown stoppage concerns. It was clear the incompatibility of the two control systems when adapted to the same equipment and needing to work together. Thereby, it was decided by the perennial need to carry out an upgrade in order to simultaneously standardize the amend type control, other malfunction source previously identified by Preventive and Curative maintenance teams, and adjust as much as possible the capacity / output to the new production requirements.

3.4.1. Description of the initial situation

Originally, as already explained, the device under study was, in practical terms, divided into two devices (Figure 20).

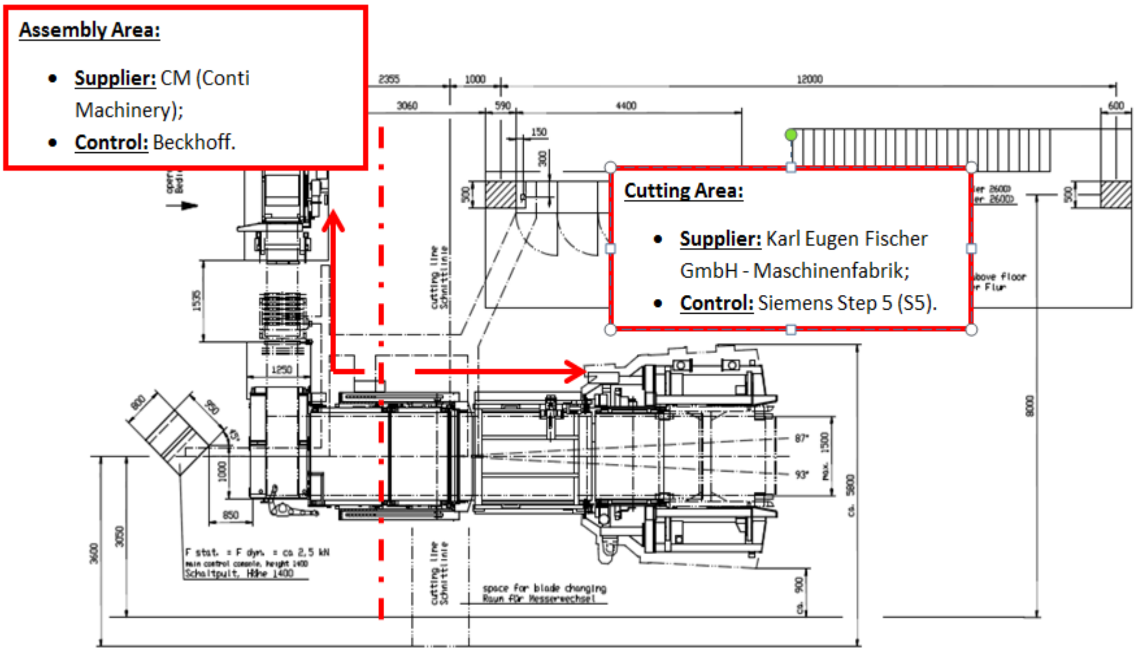

Figure 20 - Textile Cutter Top Illustration (before upgrade)

Note also the difficulties felt whenever the need arose to perform the machine start up after a prolonged maintenance or production stop period, or even for different article manufacturing set-up elaboration.

Such difficulties were reflected obviously in production lost time and scrap generated with set-ups and machine breakdown.

At mechanical level, apart from the heavy structure and difficult access to consumable and / or replaceable components, the machine original design presupposes the existence of an huge steel structure supporting the material feeding system from the buffer to the cutter. This delivery was assured by a system consisting in a suction bar with servo-powered movement that fixed and moved the textile fabric together with the conveyor (Figure 21).

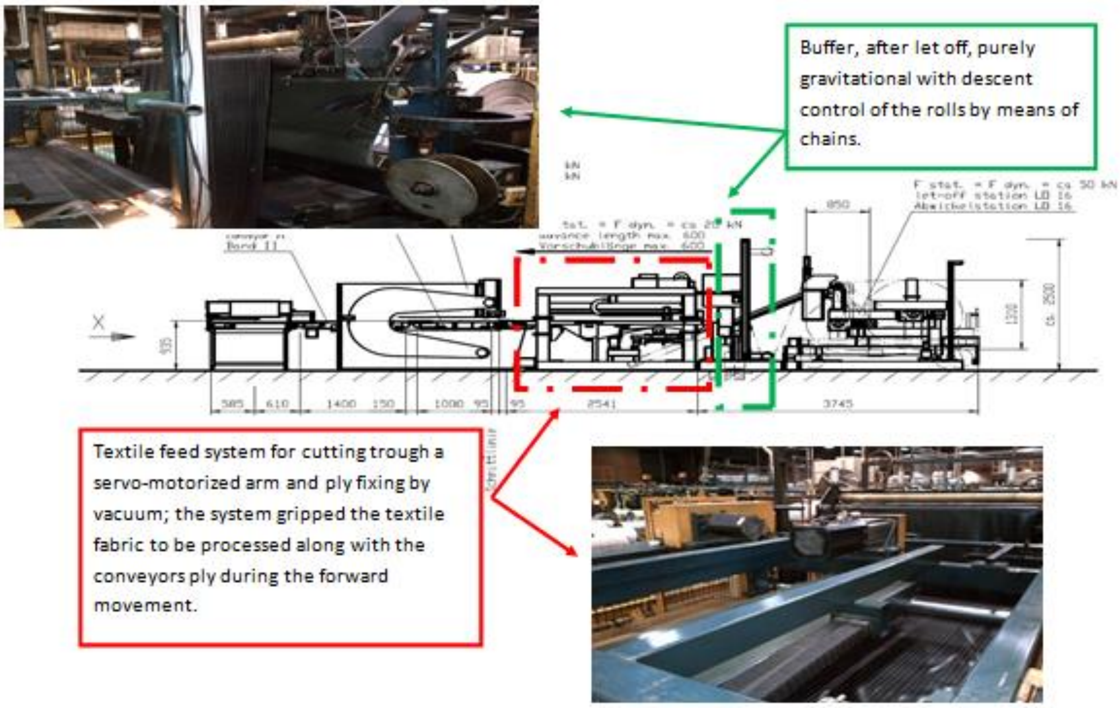

Figure 21 - Textile Cutter Side Illustration (before upgrade)

The reference for this axial movement is often lost by the system, something which required a total axes referencing and that, as a result of Siemens S5 control system associated to a completely outdated command cards, quickly became a painful and with heavy consequences in the maintenance indicators and production schedule.

Regarding this issue, adds still the urgent need to replace the let-off buffer responsible for the material accumulation in order to assure the continuous feeding to the cutter, since it is a structure which, as a result of age and use, indicated severe signs of wear with diminished adjustment possibilities that, in some components, did not exist. This was an inevitable source of the misalignment before the cutting conveyor entrance and, therefore, of the wrinkle that therein was formed in the handling of some materials which would eventually culminate in widths cutting differences beyond the specified tolerances, or scrap.

3.4.2. Goals to be achieved

Regarding the upgrade planned, it was defined as main objective the reduction of time lost due to failure, reducing the levels of scrap allocated to the equipment, reducing the complexity of the equipment itself through the simplification or updating of certain cycle steps, the increase in the equipment availability for production (OEE) and, ultimately, to reduce the amount of obsolete spare parts in storage.

3.4.3. Brainstorming about possible solutions - Preliminary draft

In this particular case, the internal meetings held for defining the plant specifications that would be provided to the suppliers for quotation, focused on specific points because it was known exactly the actions needed to perform in order to achieve the proposed objectives.

In this sense, only encouraged the holding of meetings, initially internal in order to define together with the other concerned departments (Production, Quality, Process and Safety) requirements to demand and, secondly, with Central Engineering colleagues in order to pass on our intentions and thus provide them with the necessary information (through the Requirement Book) to start the tendering and adjudication to an outside supplier stage.

Thus, the actions below were set as a basis for the upgrade:

- Centre all the control in *Beckhoff* technologie / to replace Siemens *S5;*
- Centre all safety in a *TWIN SAFE* PLC*;*
- Replacing Drives *611* (*Siemens*) and *Indromats* by *Sinamics;*
- Replacing *FT5* motors and *Indromats* by *Sinamics;*
- Reconditioning all gear boxes and replace the obsolete ones;
- Adjusting the visualisation as for specified in the Continental Machine Equipment Standard (*MES).* This document has all the specifications (Mechanical, Electrical and Control & Drives) required for any equipment supplied to the Continental group, there is one MES for each and every different equipment operating in the Continental plants;

3.4.4. Project for the selected solution

From the meetings held internally and with the Continental central engineering team, resulted a summary table with the requirements considered as essential for intervention in matter, later integrated into the Requirement Book's chapter "Plant Requirements", and from which is presented a small excerpt, as follows (Figure 22:

Item	Upgrade Content	Status Re-Use	 New	Scope Supplier	 Conti
A	**Hardware engineering with following options:** **1) Replace S5 Cabinet (Cutter, Letoff) and Beckhoff Cabinet (Transfer, Pick&Place, Splicer, Perforator and Windup)** **2) Replace S5 Cabinet and upgrade of existent Beckhoff Cabinet (Drives, I/Os, IPC and Safety)**			x	
B	**Software Engineering**				
B1	HMI			x	
B2	Control program (PLC+System Manager+TwinSAFE +integration of SFI and local recipe system)			x	
C	**Electrical equipment:**				
C1	• **New Main Electrical cabinet including installed parts:** ➢ Main switch for power supply ➢ Main control voltage supply ➢ Control voltage supply 24 V DC/ UPS ➢ Busbar system with various fuses ➢ Control, switching and protection devices ➢ Emergency stop circuit/TwinSafe ➢ IPC based control system, ➢ I/O modules ➢ Frequency drives/servo drives ➢ Network switch ➢ … ➢ Installation material (e.g. plugs, cable glances, terminals,..) *** Note: Scope above to be agreed with Continental for option 1 and 2 taking in account optimisation in terms of hardware price and installation**		X*	x	
C2	• **Main Operator Panel** ➢ HMI operator panel ➢ Push-button extension station with Emergency Stop ➢ Panel support/ holder		x	x	

Figure 22 - Upgrade specifications

These are the indications given to suppliers at contest as for the work to consider in the proposal to be submitted.

In the winning proposal (presented by a local supplier), the system architecture, as well as hardware and software components were chosen to provide the best service possible, keeping in mind that the system would had to be enlarged and upgraded, so the global solution should not be limitative in terms of production increase and product complexity rise.

According to the technical documentation of the contest, it was proposed Beckhoff architecture for the automation system and a Siemens Solution based in WinCC flexible for Supervisor System. This choice solves all the needs explained in the technical description and keeps the global system open for future needs (Figure 23).

Figure 23 - Automation Architecture

The system proposed was based on WinCC Flexible from Siemens. The communications between the SCADA system and the Programmable Logic Controller (PLC) program would be made through an Object Linking and Embebing for Process Control (OPC) Server included on this proposal.

The chart of items to be included in this upgrade can be seen in Figure 24.

Item	Qtd	Area	Use Existing Reducer	Supply New Reducer	New Servo	New gear box
1		LET Off Station				
1.1	1	Motor Edge left side	x		--	
1.2	1	Motor Edge right side	x		--	
1.3	1	Motor Letoff Material	x		1FK7084-3BC71-1DB0	
1.4	1	Motor Liner Winder Letoff	x		1FK7084-3BC71-1DB0	
1.5	1	Servomotor ("Advance System")	x		1FT7084-5AF70-1DB0	
1.6	1	Conveyor ("Advance System")	x		1FT7105-5AF70-1DB0	
2		Transfer System				
2.1	1	Motor Transfer System Drive Suction Beam		x	1FK7080-2AF71-1QH1-Z J03	Redutor Planetário acoplado tipo SP 100S-MF1-5
3		Splice Unit				
3.1	1	Motor Belt Conveyor		x	1FK7101-2AF71-1QH1-Z J13	Redutor Planetário acoplado tipo SP 100S-MF1-20
3.2	1	Motor Belt Table		x	1FK7083-2AF71-1QG1-Z J05	Redutor Planetário acoplado tipo SP 100S-MF1-7
3.3	1	Motor Pull Roll		x	1FK7083-2AF71-1QG1-Z J09	Redutor Planetário acoplado tipo SP 100S-MF1-10
4		Perforator				
4.1	1	Motor Prickler	x		1FK7081-2AC71-1QA0	
5		Wind Up				
5.1	1	Motor Wind Up	x		1FK7081-2AC71-1QB0	

Figure 24 - List of equipments to Install

3.4.5. Accomplished Real Gains

In general terms, the gains were those previously discussed as requirements, which will be further presented as Control and Mechanical.

Thus, the gains regarding the Control are:

- New electrical cabinet;
- Replacement of the obsolete components (drives, motors, switches, etc.);
- Now the different areas of the machine are controlled by a single system (*Beckhoff*) (F*igure 25*). Due to this type of control and visualization, which is common to the other machines from the industrial park, there was also a gain concerning training, since the Curative and Preventive Maintenance teams are using this schematic software.

*F*igure 25 - New visualization and control panel

- That particular feature is reflected in the lower intervention times for Troubleshooting (Lost Times by breakdown) because, by being familiarised with the type of software organization, the technicians from the maintenance teams take less time to find and solve a breakdown (Figure 26);

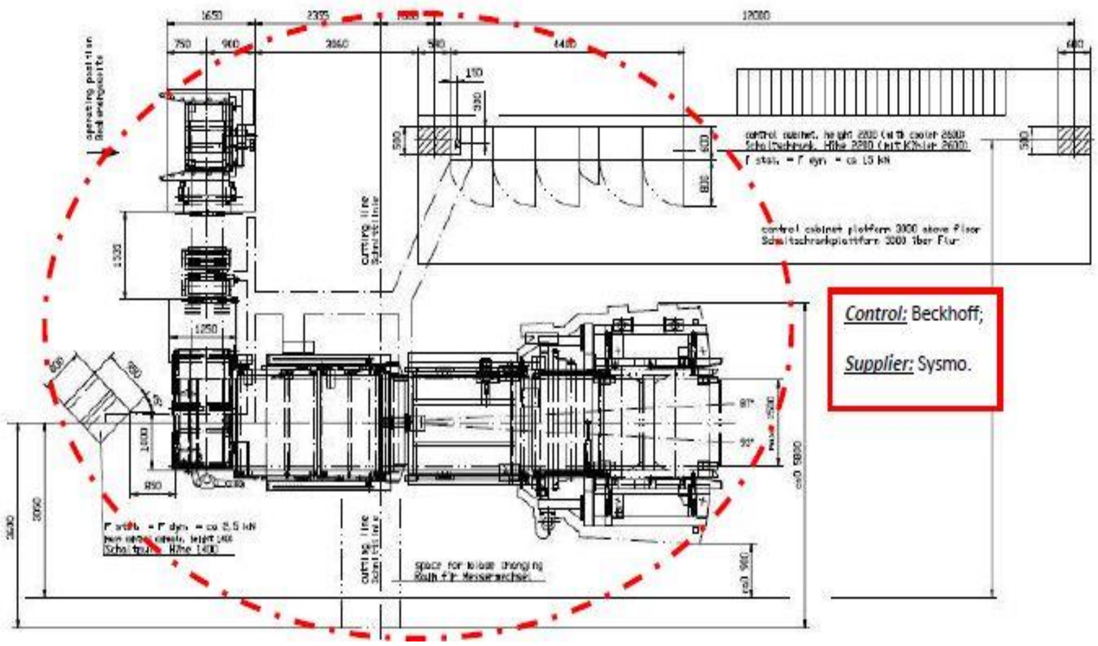

Figure 26 - Textile Cutter top illustration (after upgrade)

Regarding the mechanical part, the cutting area was the most upgraded, being also the one which needed more changes.

Thus, we can point as major improvements those seen with the removal of the textile transport to the cutter holder structure and the complete restructuring of the post let-off buffer, which has ensured the production stability before cutting regardless of its thickness, reducing so the constant jams and resultant scrap (Figure 27).

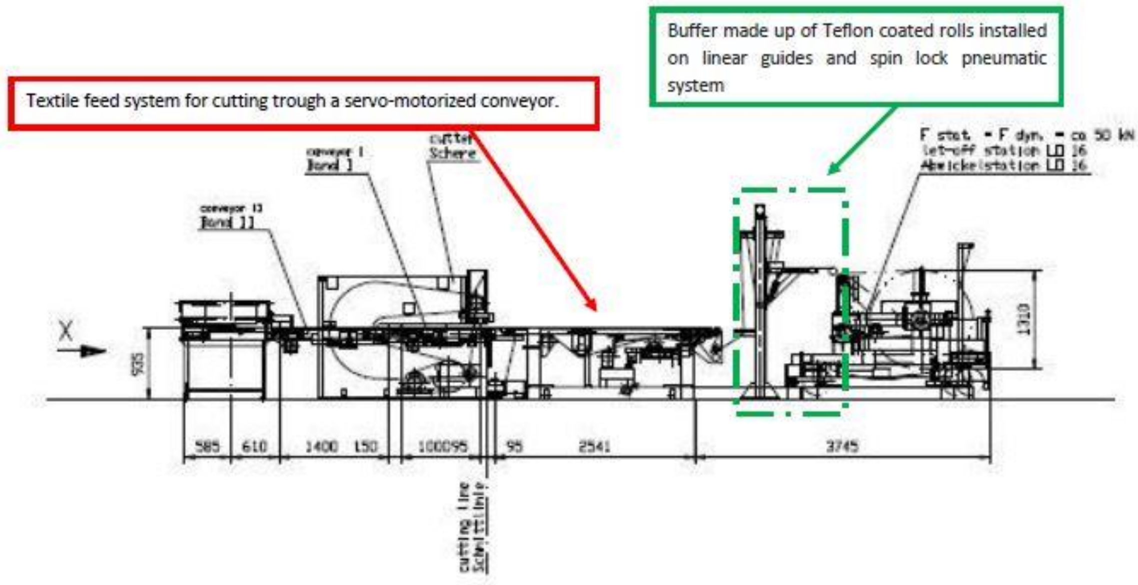

Figure 27 - Textile Cutter side illustration (after upgrade)

The safety aspect should be also noted, therefore taking the opportunity of dwell time and budget available, the safety specifications of the machine was also adjusted to the parameters currently required by law. Thus, in addition to the concept of the safety control software, physical barriers with switches / locks complying with the legal requirements have also been installed, as can be seen below (Figure 28):

Figure 28 - Top view of the Textile Cutter cutting area (after upgrade)

3.4.6. Investment Required

As already mentioned, in order to carry out the proposed works, two suppliers were consulted: a local one and the machine manufacturer.

The selection turned out to be within the domestic supplier in as much as, in addition to technical skills already widely demonstrated through the long-time partnership with the Continental Mabor, the fact that our country has lower operating costs when compared with Germany, allowed its commercial proposal to be cheaper than the one presented by the German Competitors in over 50%. Thereby combining the costs proposed by the supplier to the internal estimated ones allocated to the actions that would be at Continental Mabor charge, a total budget for the upgrade was requested and approved by the management.

3.4.7. Payback Time

In this particular case, the concept of "time required to recover the investment" is not applicable since this intervention arises from a need identified by the Engineering Department through the application of the maintenance model analysed in this thesis, then approved by the production department and the other departments involved and, in 2012, integrated in the budget for "Major Repair" for 2013 (general maintenance budget assigned annually to each Continental plant, which is then divided into several individual projects). Therefore, although internally be considered as a maintenance cost, for tax purposes it is considered as an investment, which leads to substantial fiscal counterparts and benefits for the plant and, consequently, for the group.

3.4.8. Summary of Results

Before proceeding to the explanation of the results obtained with the methodology in study and respective action which took place and is presented in this paper as a case study, it should first be realized the volatility associated with this branch of industry.

Thus, in an easily perceivable way we describe in general terms how the Continental AG group distributes the needs or volumes necessary to satisfy the markets, by the group's various factories.

At each factory, depending on its production capacity and number of articles (different types / models and tire sub-branches) in production, it is assigned a "quote" of production, which is an annual quantity of tires to be injected in the market, being estimated according to its variation and always calculated on, at least, a year in advance.

However, as many others car and financial market from which the tire market totally depends, also suffer sudden and unusual variations, which sometimes requires an extra effort from the tires factories to ensure the required production outputs quotes as, on the other hand, the ability to slow down and adapt the direct costs concerned to a sudden and unexpected decrease tires demand.

Thus, it is easy to understand why, even when you analyse namesakes periods between two consecutive years, not always the results obtained represent the checked reality.

Thus there was exactly found this phenomenon when examining the results pre and post intervention on the machine, that is, analysing the production levels assigned to this particular equipment we could be taken to conclude that the total production of the factory and its turnover fell from 2013 to 2014, however, this could not be further far from the truth, in so far as the year 2014, not only increased the number of units produced as also increased even more significant of the billing levels result, not from the general increase in production but, above all, the increased production of articles of incremented value by, which, in the case of a tire factory, translates in the increase of high-performance tires production.

This increase in number of the different articles (internally designated as “complexity” or “mix”) that prophesied the reduction in levels of productivity associated with the machine in analysis of the year 2013 to 2014, as shown in the picture took from the production management platform of Continental Basic Data Acquisition System (CBDAS) in the next figure (Figure 29).

In conclusion, the decrease verified does not derive from overall lower production levels, once, as it is clear, both the total and other months results grown in 2014 but, from the attempt of distribution in this particular month of the various articles in production by the four machines that make up the textile cutting division, so as to minimize the production losses allocated to set-ups.

	Sum of Quant.		
Months	**2013**	**2014**	**Grand Total**
T 02	**6407288**	**7688748**	**14096036**
Jan	688857	655840	1344697
Fev	586325	698656	1284981
Mar	629125	743616	1372741
Abr	654617	631176	1285793
Mai	665788	768426	1434214
Jun	644042	725852	1369894
Jul	666597	691255	1357852
Ago	537438	531849	1069287
Set	714966	669247	1384213
Out	34837	671487	706324
Nov	319370	608108	927478
Dez	265326	293236	558562
Grand Total	**6407288**	**7688748**	**14096036**

Figure 29 - Textile Cutter machine #02 2013 and 2014 production (data removed from CBDAS) (m)

Moving to the comparison between the results recorded before, the upgrade execution (September 2013) with those obtained in the next year (Sep/2014):

1. Time Losses for Breakdown:

   From the SAP management software were collected the following data related to the time lost by breakdown in September/2013 (Figure 30).

Denominação	Descrição	InicioAvar	HoraInicioAvar.	Fim avaria	Hora fim avaria	Duraç.parada	Unidade
Máquina Cortadora de Tela Textil nº: 2	mecanica	01-09-2013	10:29:11	01-09-2013	10:49:11	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	01-09-2013	18:19:06	01-09-2013	18:39:00	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	04-09-2013	21:46:07	04-09-2013	22:01:07	0,25	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	04-09-2013	23:18:10	04-09-2013	23:33:10	0,25	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	05-09-2013	09:12:42	05-09-2013	10:47:42	1,58	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	06-09-2013	10:55:04	06-09-2013	11:20:04	0,42	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	06-09-2013	16:53:16	06-09-2013	17:08:16	0,25	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	06-09-2013	19:16:20	06-09-2013	19:31:20	0,25	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	07-09-2013	08:33:46	07-09-2013	08:43:46	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	07-09-2013	20:18:42	07-09-2013	20:18:42	0,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	07-09-2013	20:53:07	07-09-2013	21:30:07	0,62	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	08-09-2013	02:00:51	08-09-2013	02:20:51	0,33	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	08-09-2013	09:51:37	08-09-2013	10:21:37	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	10-09-2013	00:04:46	10-09-2013	00:14:46	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	10-09-2013	08:00:00	10-09-2013	08:00:00	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	10-09-2013	08:29:23	10-09-2013	09:19:23	0,83	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	10-09-2013	16:35:03	10-09-2013	16:45:03	0,17	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	13-09-2013	04:10:08	13-09-2013	04:10:08	0,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	15-09-2013	19:04:49	15-09-2013	19:34:49	0,50	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	17-09-2013	00:38:52	17-09-2013	01:23:52	0,75	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	19-09-2013	08:24:35	19-09-2013	08:34:35	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	28-09-2013	08:14:48	28-09-2013	08:24:48	0,17	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	29-09-2013	12:32:35	29-09-2013	12:32:35	0,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	30-09-2013	16:33:31	30-09-2013	16:43:31	0,17	H

Figure 30 - September 2013 Textile Cutter #02 breakdown time losses (data removed from SAP) (h)

Of which resulted the summary figure below (Figure 31):

	SAP Values	***Loss Time***	***% Total Time***
Total	8,21	8h13	100%
Electrical	4,84	4h50	59%
Mechanical	3,37	3h23	41%

Figure 31 - September 2013 Textile Cutter #02 global breakdown time losses (data removed from SAP) (H)

Analysing the presented figures, we can conclude that, in September.2013, the time lost by electrical breakdown was similar to that caused by mechanical causes.

This brings us to the low levels of complexity/mix recorded in 2013, when compared with 2014, which translates to greater stability in production as a result of the reduced need to perform set-ups.

2. <u>Levels of Scrap generated by Breakdown:</u>

The scrap values allocated to the machine in study in September 2013 (before the upgrade) were as presented below (Figure 32):

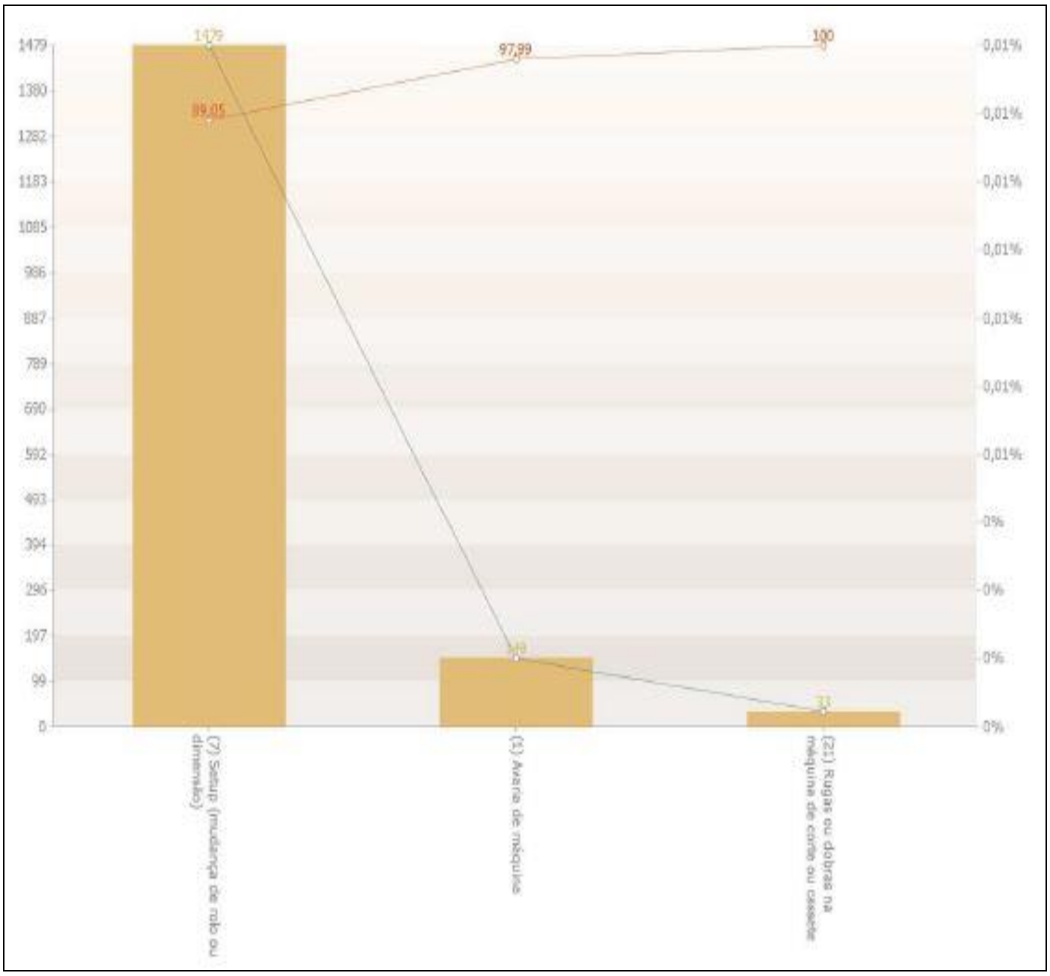

Figure 32 - September 2013 Textile Cutter #02 scrap analysis (data removed from scrap attack platform)(kg)

The data collected, when grouped as in the table below, allow us to conclude that the time lost and nature of the damage observed in September 2013 represents only a small part (8.9%) of the causes associated scrap generation (Figure 33).

	Quantity		%
Total:	1660,9	kg	100,0%
Setup:	1479	kg	89,0%
Breakdown:	148,5	kg	8,9%

Figure 33 - September 2013 Textile Cutter #02 global scrap analysis by root cause (data removed from scrap attack platform)(kg)

The great booster of scrap values checked was, without a doubt, the scrap generated during the set-ups, i.e., the amount of damaged material during machine setting to the production of a new article and/or taken as needed to make adjustments after an intervention by failure.

This difficulty can be associated to the fact that machine initially had two distinct types of control which co-existence was not always peaceful; this meant a tremendous difficulty to parameterize and synchronize the production start-ups.

After the intervention carried out, analysed the results obtained during the same period immediately after the intervention (September 2014) below indicated, we can conclude the following (Figure 34):

1. <u>Time Losses for Breakdown:</u>

Denominação	Descrição	InícioAvar	HoraInício Avar.	Fim avaria	Hora fim avaria	Duraç. parada	Unidade
Máquina Cortadora de Tela Textil nº: 2	mecanica	01-09-2014	17:34:55	01-09-2014	17:49:55	0,25	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	04-09-2014	04:56:35	04-09-2014	04:56:35	0,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	09-09-2014	10:35:32	09-09-2014	10:50:32	0,25	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	09-09-2014	21:02:44	09-09-2014	21:42:44	0,67	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	10-09-2014	04:52:31	10-09-2014	04:52:31	0,00	H
Máquina Cortadora de Tela Textil nº: 2	electrica	10-09-2014	17:31:53	10-09-2014	17:56:53	0,42	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	12-09-2014	22:12:15	12-09-2014	23:12:15	1,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	13-09-2014	19:56:42	13-09-2014	20:16:42	0,33	H
Máquina Cortadora de Tela Textil nº: 2	electrica	14-09-2014	08:48:34	14-09-2014	08:48:34	0,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	14-09-2014	14:47:54	14-09-2014	15:07:54	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	14-09-2014	22:15:18	14-09-2014	22:15:18	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	15-09-2014	17:11:06	15-09-2014	17:31:06	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	15-09-2014	22:51:12	15-09-2014	23:10:12	0,32	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	08:07:22	16-09-2014	08:07:22	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	09:08:20	16-09-2014	09:08:20	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	09:42:21	16-09-2014	10:02:21	0,33	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	16-09-2014	10:45:47	16-09-2014	10:55:00	0,15	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	11:12:34	16-09-2014	11:22:34	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	12:02:45	16-09-2014	12:12:45	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	15:26:26	16-09-2014	15:46:26	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	16:26:47	16-09-2014	16:56:47	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	21:24:50	16-09-2014	21:54:50	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	16-09-2014	21:50:59	16-09-2014	22:20:59	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	17-09-2014	12:34:24	17-09-2014	12:54:24	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	08:14:03	18-09-2014	08:44:03	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	14:45:49	18-09-2014	15:00:49	0,25	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	16:43:13	18-09-2014	16:53:13	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	17:21:50	18-09-2014	17:46:50	0,42	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	19:42:13	18-09-2014	20:15:00	0,55	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	20:16:06	18-09-2014	20:30:06	0,23	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	20:56:04	18-09-2014	20:56:04	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	18-09-2014	21:35:09	18-09-2014	21:35:09	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	19-09-2014	08:56:20	19-09-2014	09:16:20	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	19-09-2014	11:25:23	19-09-2014	11:45:23	0,33	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	19-09-2014	21:01:44	19-09-2014	21:21:44	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	21-09-2014	21:22:55	21-09-2014	21:40:55	0,30	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	22-09-2014	01:52:56	22-09-2014	02:12:56	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	22-09-2014	03:02:39	22-09-2014	03:02:39	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	22-09-2014	08:48:21	22-09-2014	09:00:21	0,20	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	22-09-2014	11:27:11	22-09-2014	11:37:11	0,17	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	22-09-2014	13:16:47	22-09-2014	14:16:47	1,00	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	23-09-2014	23:11:49	23-09-2014	23:41:49	0,50	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	24-09-2014	09:02:53	24-09-2014	09:22:53	0,33	H
Máquina Cortadora de Tela Textil nº: 2	mecanica	24-09-2014	14:38:04	24-09-2014	14:38:04	0,00	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	26-09-2014	00:57:01	26-09-2014	01:17:01	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	26-09-2014	01:18:48	26-09-2014	01:48:48	0,50	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	26-09-2014	02:10:51	26-09-2014	02:30:51	0,33	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	26-09-2014	08:20:34	26-09-2014	09:00:00	0,66	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	27-09-2014	11:20:26	27-09-2014	12:00:26	0,67	H
Máquina Cortadora de Tela Textil nº: 2	eletrica	28-09-2014	02:53:52	28-09-2014	02:53:52	0,00	H

Figure 34 - September 2014 Textile Cutter #02 breakdown time losses (data removed from SAP) (h)

From the above listed data analysis, resulted the breakdown time summary in the figure presented below (

	SAP Values	Breakdown Time	% Total Time
Total	15,31	15h19	(...)
Electrical	11,17	11h10	73%
Mechanical	4,14	04h09	27%

Figure 35):

Figure 35 - September 2014 Textile Cutter #02 global breakdown time losses by route cause (data removed from SAP) (h)

Here we conclude by the increase of electrical damage in relation to the same period of last year, that reality associated to the intervention carried out has not improved the breakdowns downtimes in that respect, however, it is essential to understand also what was changed on the production planning when compared to the period prior to the upgrade implementation.

Indeed, it is through the analysis of the scrap levels recorded during September of 2014 that we can take some more realistic conclusions (Figure 36):

2. <u>Levels of Scrap generated by Breakdown:</u>

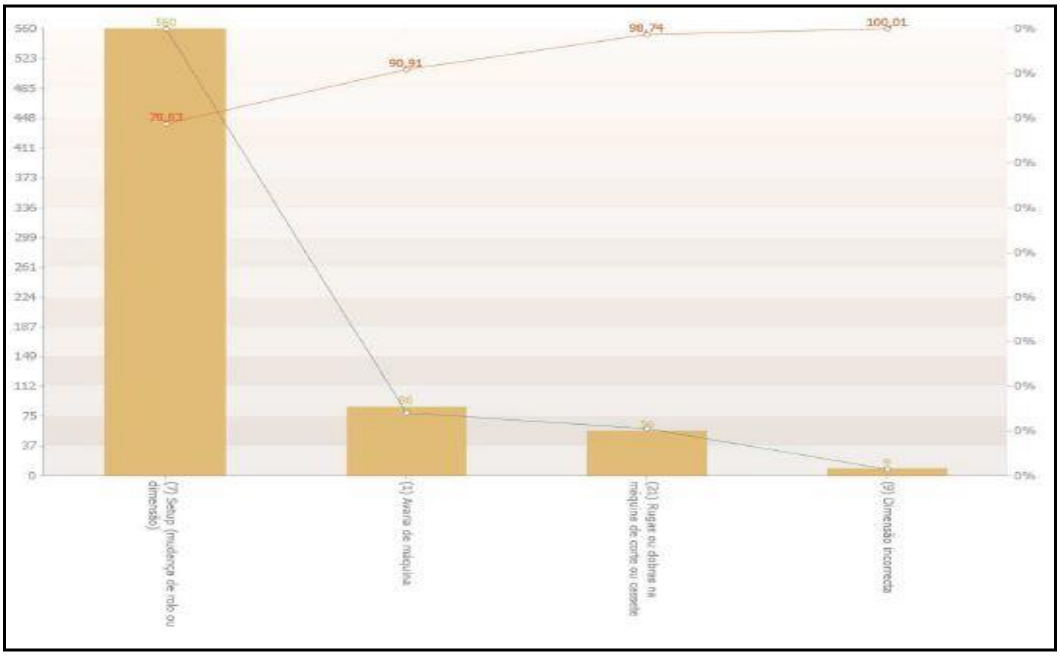

Figure 36 - September 2014 Textile Cutter #02 scrap analysis (data removed from scrap attack platform)(kg)

Once again, the analysis to the graphic showed above resulted in the following summary figure (Figure 37):

	Quantity		**%**
Total:	710,45	kg	100,0%
Setup:	560,05	kg	78,8%
Breakdown:	85,8	kg	12,1%

Figure 37 - September 2014 Textile Cutter #02 global scrap analysis by root cause (data removed from scrap attack platform)(kg)

Analysing the summary table of failure generated scrap, apart from a slight increase, we realize that, despite the decreased difference to the scrap generated by setups, the total amount of scrap for the month of September dropped dramatically compared to the same period in the previous year, regardless of the increase in the number of articles (mix) in production.

We can then conclude that the scrap generated by failure in September 2014 decreased to almost a 1/3 of the values checked on the same period of 2013, despite the implications related to the fluctuations of the levels and nature of articles in production. We are also driven to conclude that the range of articles in production had a direct influence in the time lost through malfunction, but not in production levels as it would be initially expected.

3.5. Proposed Model for Application in Other Companies

So we are proposing a model of project team integration in the traditional maintenance according to the following general assumptions (Figure 38):

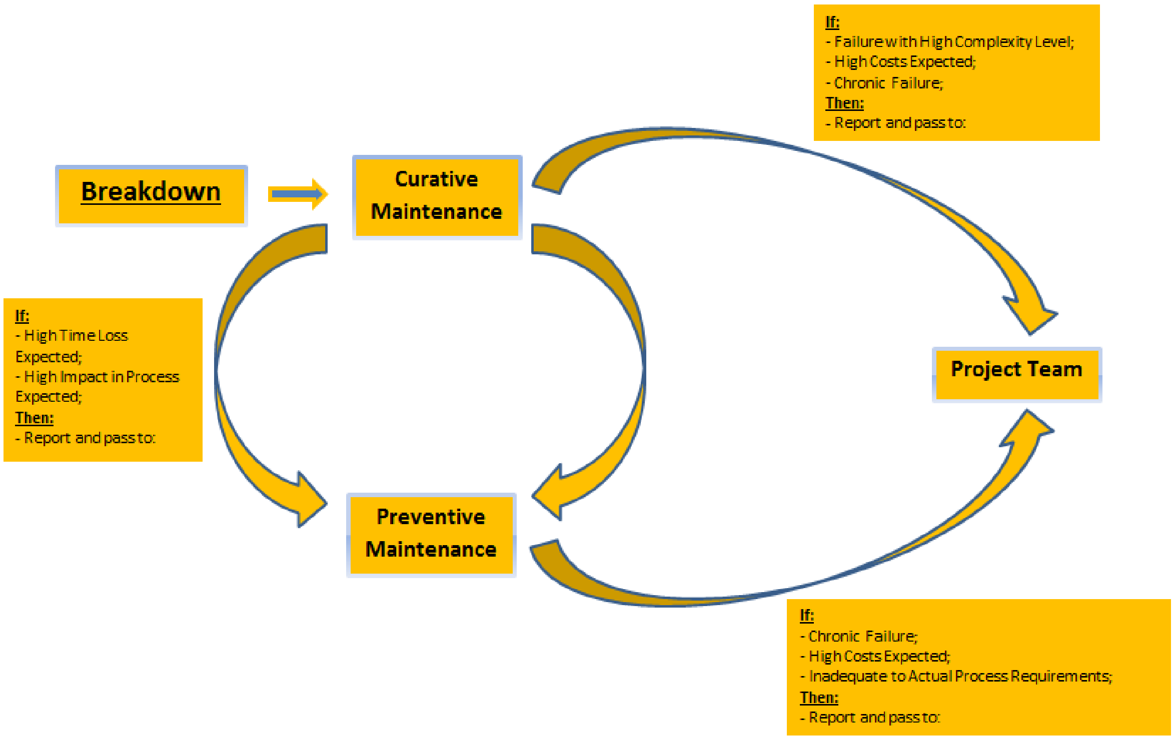

Figure 38 - General approach flux flow

Hence, in general terms, the integration of the project team in the Classic Maintenance flow will occur as follows:

After the occurrence of a malfunction, the first intervention will always be made by the Curative Maintenance team that, if the intervention is complex and/or expensive, will try to just ensure the start up for production of the machine (even that in a conditioned way), passing the teams analysis / diagnosis to the preventive maintenance teams. In the case that the malfunction does not fit in the check list of the preventive maintenance or the costs associated are too high regarding the maintenance proposed objectives, it will be forwarded to the Project Team.

This way, the breakdown will be properly diagnosed and quoted and, even, in conjunction with other departments may be included other improvements or updates necessary to the production process in analysis. The defined requirements will be included in a specification and seen as an upgrade action subject to an investment project with decoupled costs usually allocated to maintenance.

We can even tailor the proposed integration by the nature of the request in addition to the previously indicated, as are the examples presented (Figure 39):

1. By interaction with the other classic branches of maintenance:

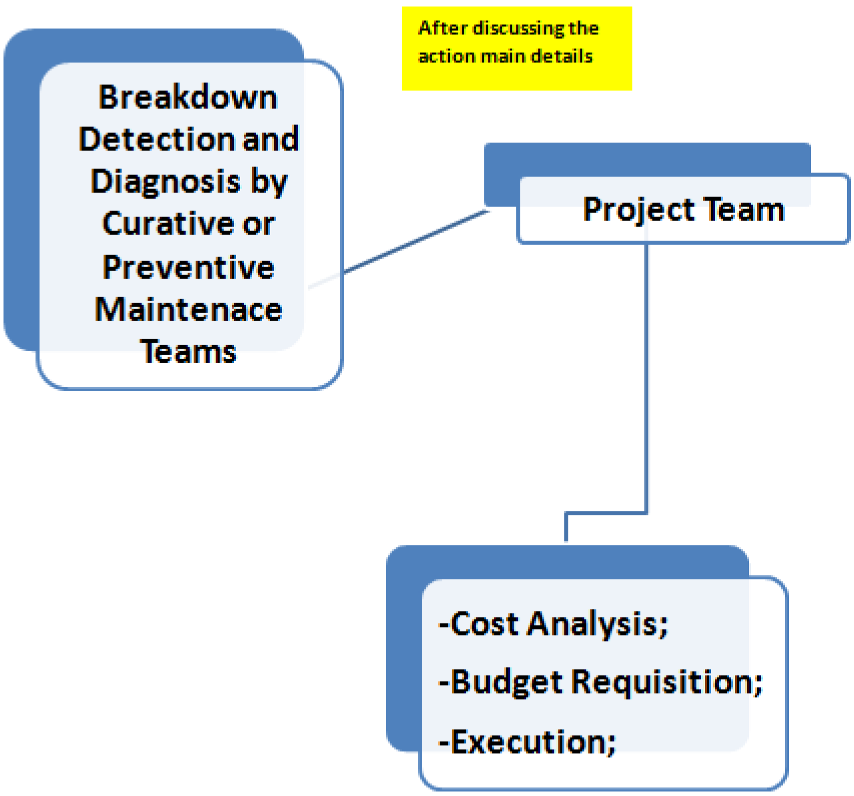

Figure 39 - By interaction with the other Maintenance Teams Approach Flux Flow

By the above represented flowchart, we can see that the Project Team intervention may also arise from a problem detected by the other maintenance teams, in particular, the Preventive Maintenance, Conditioned or even Curative Maintenance teams (Figure 40).

2. By internal customer request:

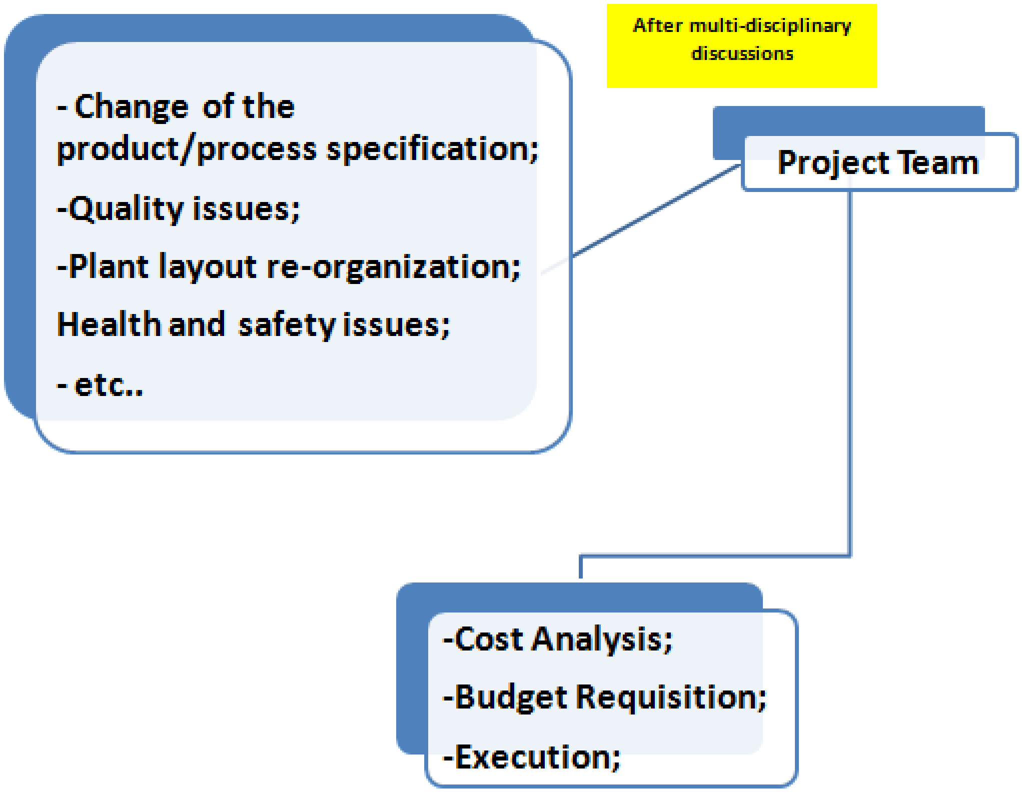

Figure 40 - By solicitation from other departments approach flux flow

The Project Team intervention may also be requested by other departments of the plant where the need arises to perform background changes in the equipment (regarding production levels, quality, security, etc.), or when the need arises to reorganize the plant layout.

So, and after multi-disciplinary discussions, changes and/or equipment relocations are carried out in accordance with the requested requirements, ensuring always the smallest possible impact on the normal maintenance crews performance, above all, in the production process.

By this way, besides ensuring a greater assertiveness in the maintenance department team intervention, allows also a more rigorous control of costs associated with the maintenance, minor time for damage and, consequently, an increase in production levels and quality of the final product.

4. Conclusions

The integration of the Project Team in the “Maintenance Classic Method” and its importance by intervening machines requiring upgrades by the moulds presented in this thesis assumes, in these days, a major importance in the company's operative results for the reasons that, in a resumed way, are presented below:

- Need of production capacity optimization as a result of the increased availability of equipment for production (OEE);
- Constant updating of equipment to new manufacturing processes;
- Guarantee of Quality high levels in the final product;
- Substantial increase of the industrial park equipment lifetime;
- Controlled maintenance costs;
- Control of spare parts amount in stock;
- Increment of assertiveness in the interventions on the machines, performed by maintenance crews;
- Possibility of clear division between Investment and Maintenance costs;
- Effective planning of maintenance, which results in the optimisation of means and resources assigned to distributed teams on the shop floor.

In conclusion, we can say that the success achieved by Continental Mabor within the Continental Group and other competitors dues, also, to the way that the Engineering Department and its divisions are organized.

There are no doubts that the assertively and efficient way that the various day-to-day problems are addressed enables the company productivity and quality levels taken as reference within the Continental Group. To this end, the establishment of a Project Team and its integration into the circle of Maintenance was essential.

In this way, in addition to create a branch of the department specializing in supporting the purchasing process and responsible for the installation of new equipment, upgrades and other background interventions in existing equipment that allow an equipment remarkable longevity and always updated to the production processes, also a more complete and reasoned approach to the day-by-day malfunctions.

In conclusion, the development and application of the presented strategy led to outstanding production levels with controlled maintenance costs.

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Outras Fontes de Informação

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